Jet Physics

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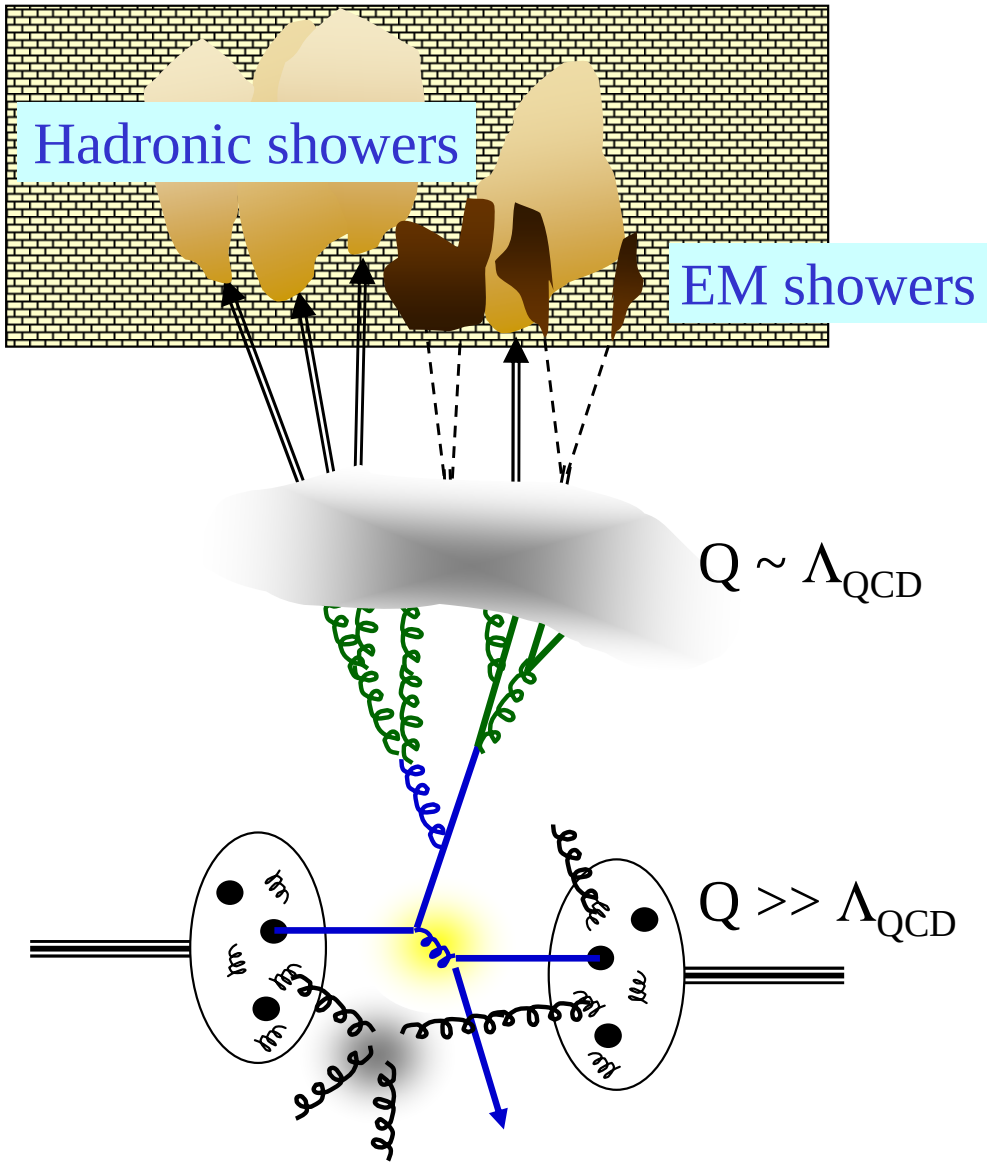
ANNECY lapp

Outline

- A bit of jet phenomenology
- Apparatus
- Results from HERA
  - Jet Production in Neutral Current Deep Inelastic Scattering
    - Inclusive Jet Production
    - Multijets
  - Jet Production in γp
- Results from the Tevatron
  - Inclusive Jet and Dijet Production
  - Beauty
    - $b\bar{b}$ Production, $Z \rightarrow b\bar{b}$, γ+b
  - Prompt γ Production
    - Inclusive γ, γ+Jets, $\gamma\gamma$
  - W+Jets and Z+Jets

"Particles, particles, particles."

Jet Production Measurements

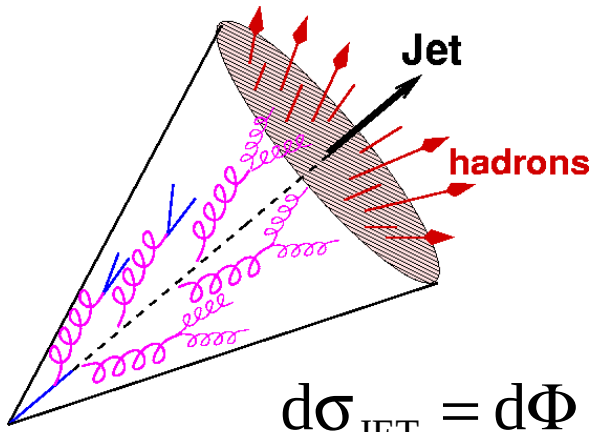


Unfold measurements to hadron level

↳ Correct for efficiency, smearing

Correct theory (pQCD) for non-perturbative effects

↳ Underlying Event, Fragmentation



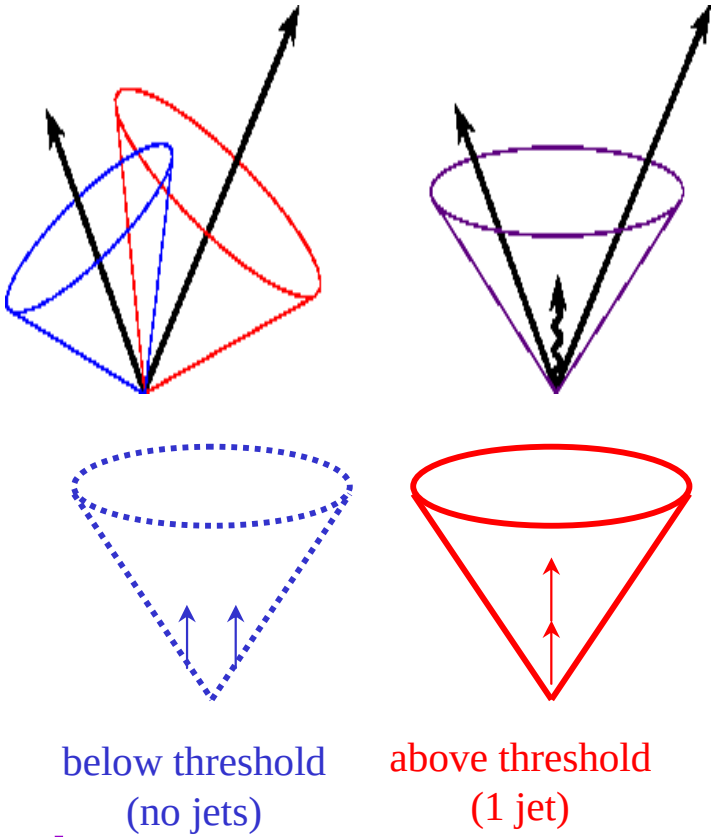
$$d\sigma_{JET} = d\Phi \, |M|^2 \, F_{JET}$$

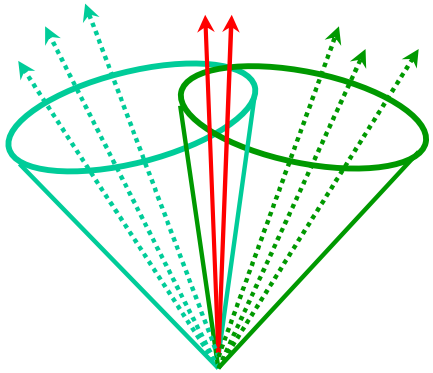
Well defined jet algorithm required

↳ At calorimeter, hadron and parton levels

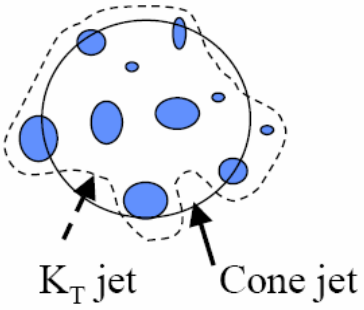
Cone Jet Algorithms and pQCD

- Iterative cone algorithms
  - Staring from seeds, iteratively cluster particles in cones of radius R_{CONE} and look for stable cones (p_T-weighted centroid)
- Infrared and Collinear Safety
  - Fixed order pQCD contains not fully cancelled infrared divergences
    - Inclusive jet cross section affected at NNLO
  - Tevatron Run II Cone Algorithm: Midpoint
    - Uses midpoints between pairs of proto-jets as additional seeds $\rightarrow$ Infrared and collinear safety restored
- Merging/Splitting
  - Emulated in NLO pQCD calculation by merging 2 partons only if they are within $R' = R_{CONE} \times R_{SEP}$ of each other
    - Arbitrary parameter R_{SEP}: prescription $R_{SEP} = 1.3$ (based on parton level approximate arguments)

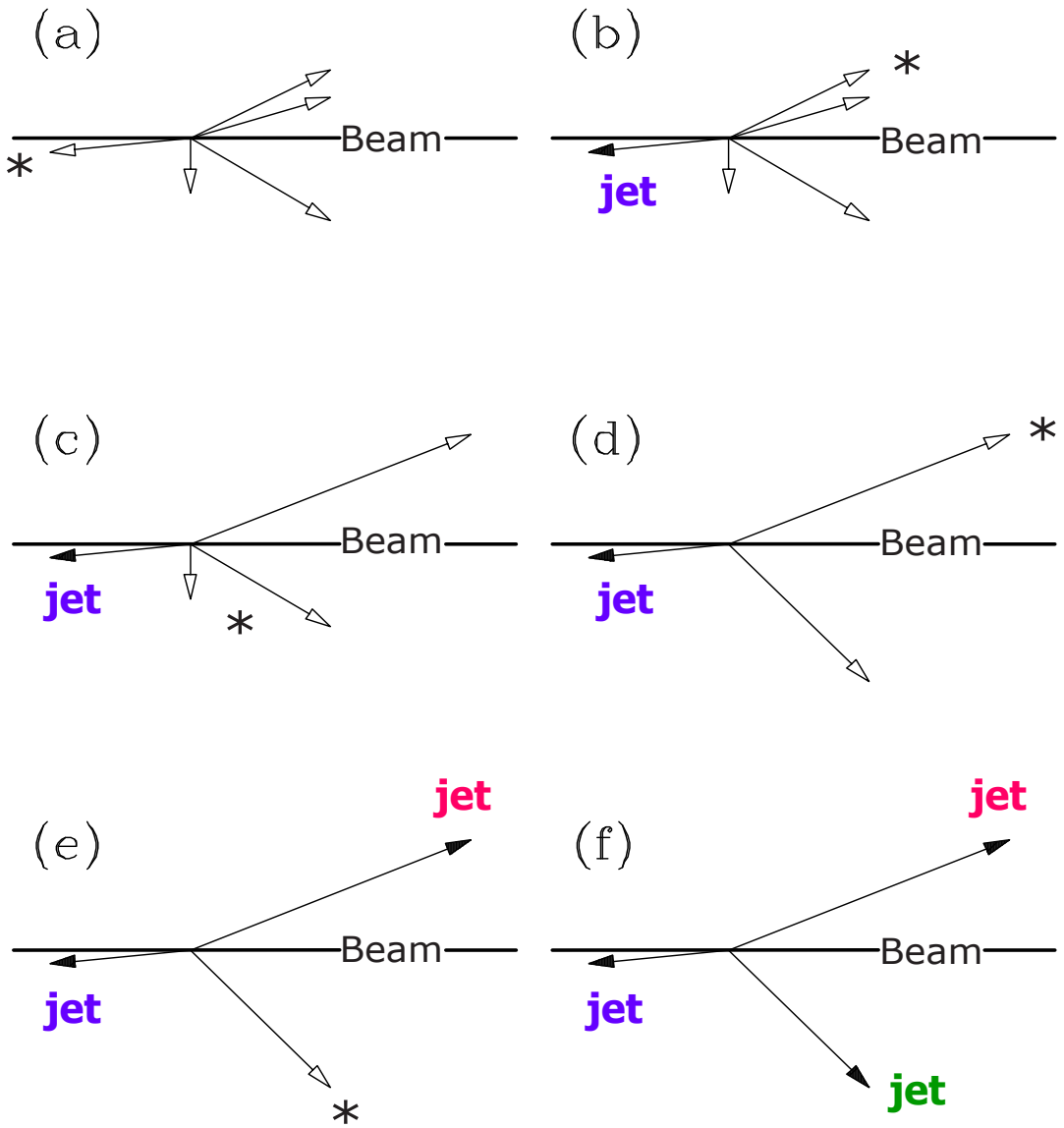




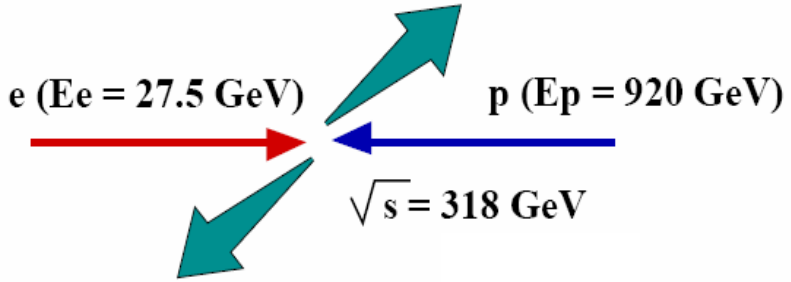
k_T Algorithm

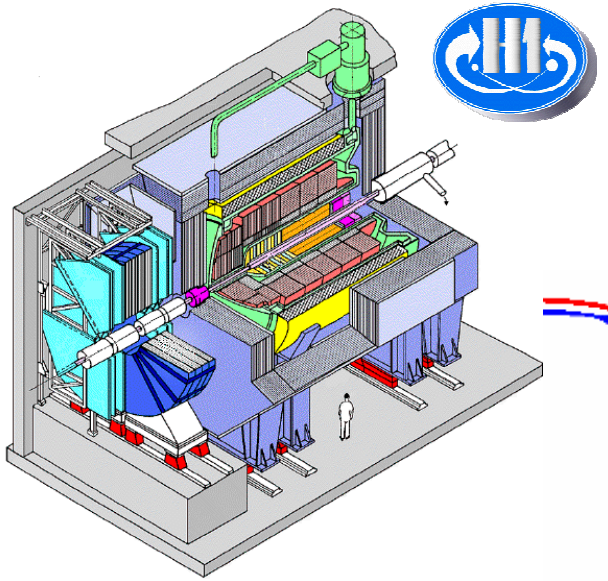


- Inclusive k_T algorithm
  - Merging pairs of nearby particles in order of increasing relative p_T
    - $d_{ij} = \min(p_{T,i}^2, p_{T,j}^2)\ \frac{\Delta R^2}{D^2}$
    - $d_{ii} = p_{T,i}^2$
  - D parameter controls merging termination and characterizes size of resulting jets
- p_T classification inspired by pQCD gluon emissions
  - Infrared and Collinear safe to all orders in pQCD
  - No merging/splitting
    - No R_{SEP} issue comparing to pQCD



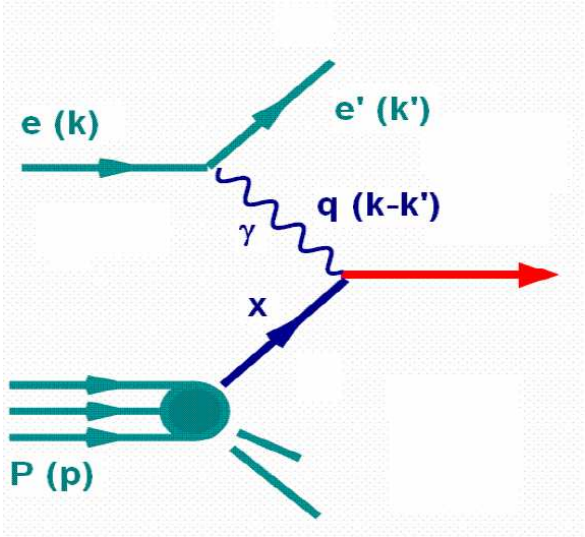
HERA - ZEUS and H1





- High Energy Running ($\sqrt{s}$ = 300 - 320 GeV)
  - Ended on March 20th, 2007
  - HERA delivered 758 pb^{-1}
  - H1 physics luminosity ~ 478 pb^{-1}
  - ZEUS physics luminosity ~ 504 pb^{-1}
- Ongoing Low Energy Running
  - E_p = 460 GeV, $\sqrt{s}$ = 225 GeV
  - Measurement on F_L
- End of HERA: July 2nd, 2007
  - HERA Fest: June 28th and 29th, 2007

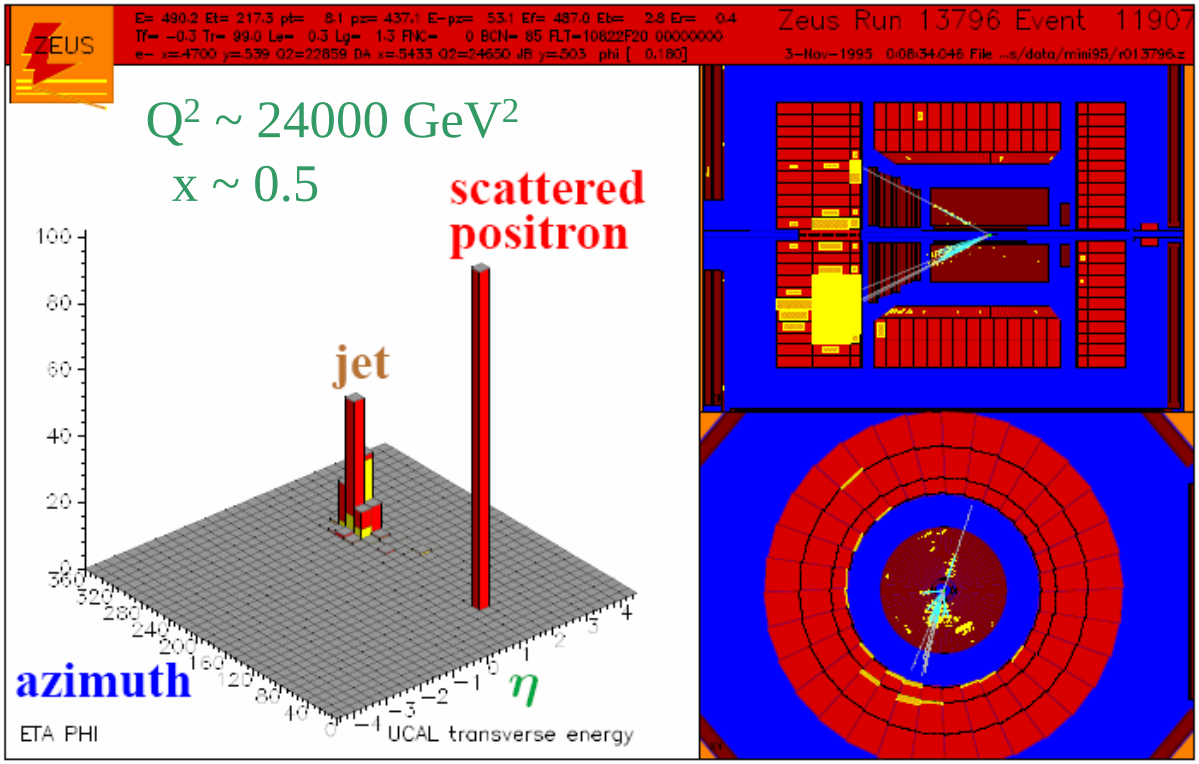
Neutral Current Deep Inelastic Scattering

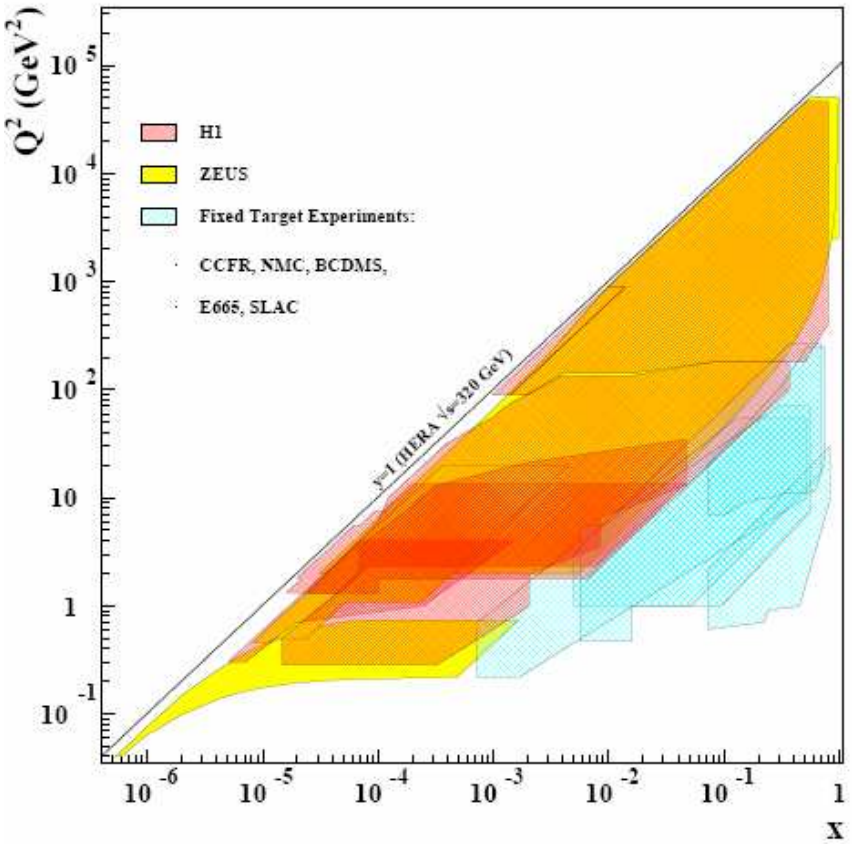


$Q^2 = -(k - k')^2$: resolution power of the photon

$x_{(Bj)} = Q^2 / (2\, p \cdot q)$: Bjorken scaling variable (momentum fraction in Quark-Parton Model events)

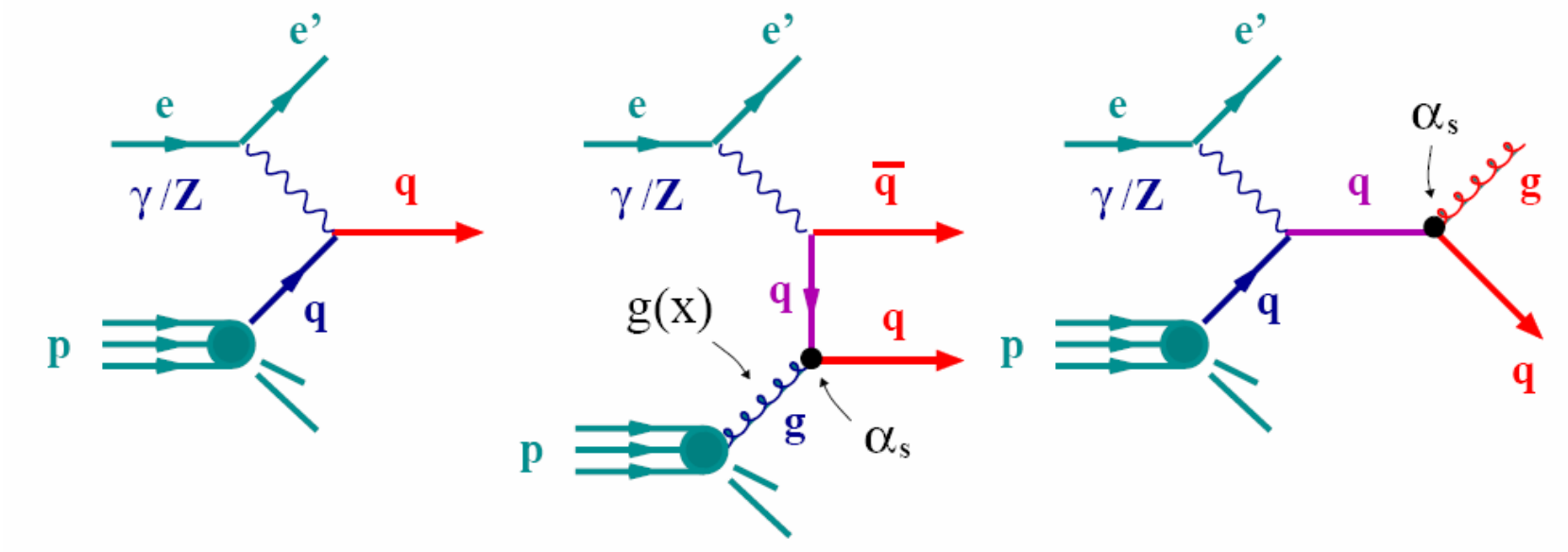
$[y = Q^2 / (x_{(Bj)}\, s)$: inelasticity variable$]$





Jet Production in Neutral Current DIS

Diagrams
up to $O(\alpha_s)$



Quark-Parton Model Boson-Gluon Fusion QCD Compton

$$d\sigma_{jet} = \sum_{a=q,\bar{q},g} \int dx\, f_a(x,\mu_F^2)\, d\hat{\sigma}_a(x,\alpha_s(\mu_R),\mu_R^2,\mu_F^2)$$

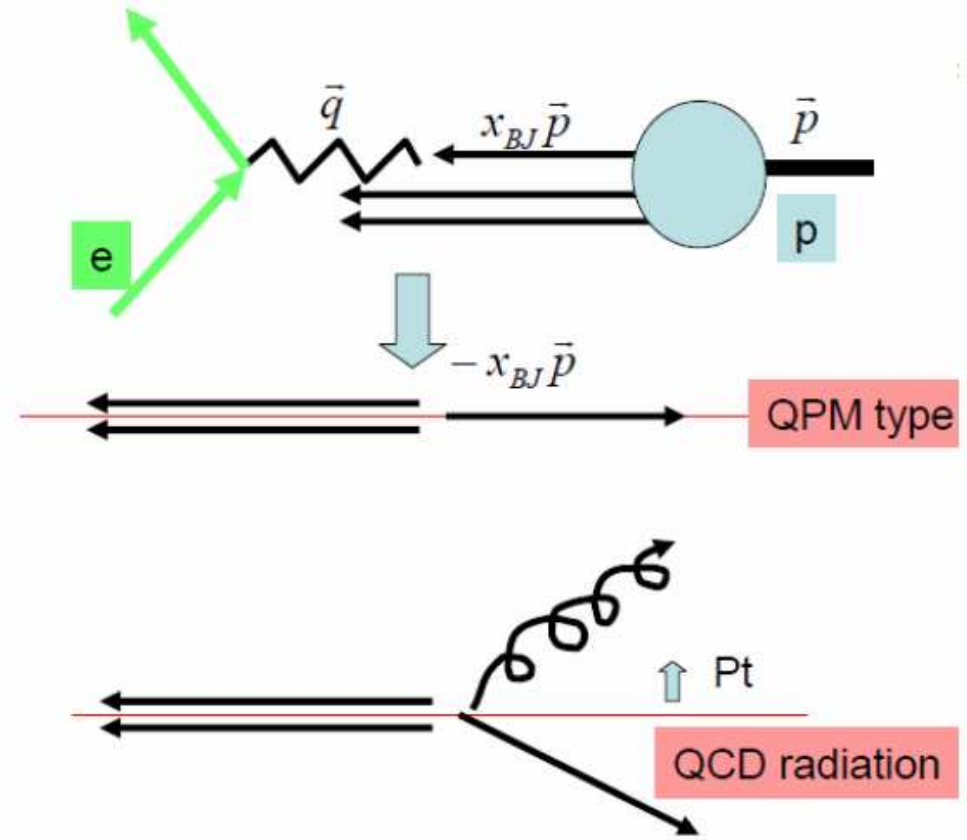
PDFs Hard Scatter

Long-distance structure of the target
↳ Determined from experiment

Short-distance structure of the interaction
↳ Calculable in pQCD

Breit Frame

$$2x_{BJ}\,\vec{p}+\vec{q}=0$$



Target Region (Proton remnants)

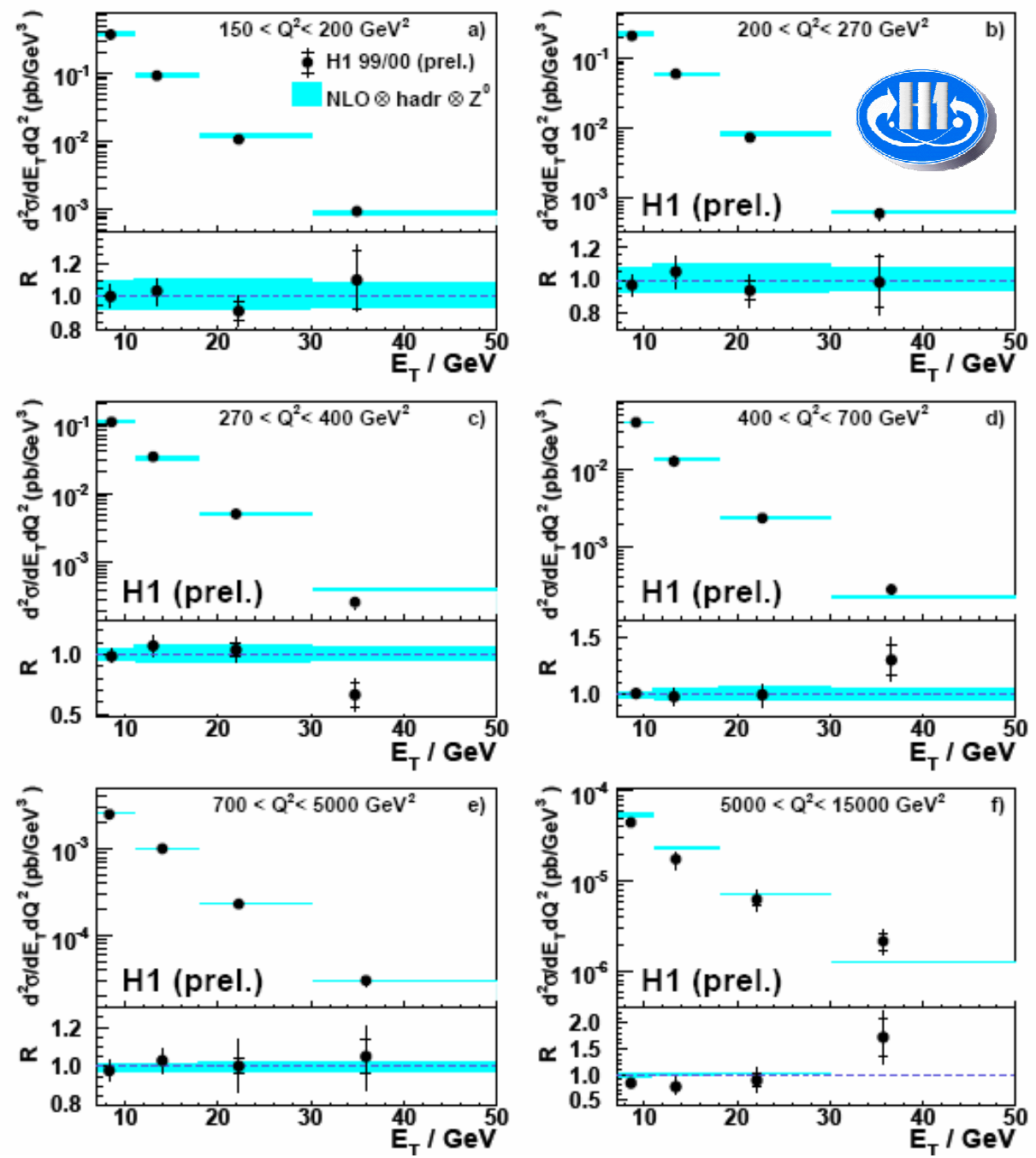
Current Region

- Virtual boson collides head-on with the proton
  - Current region can be compared to e^+e^- experiments
  - Current quark and proton remnants clearly separated
- High-E_T jet production
  - Suppression of the Born (QPM) contribution (struck quark has zero E_T)
  - Suppression of the beam-remnant jet (zero E_T)
  - Lowest order non-trivial contributions are Boson-Gluon Fusion and QCD Compton

↳ Directly sensitive to hard QCD processes (α_S)

Inclusive Jet Production in NC DIS

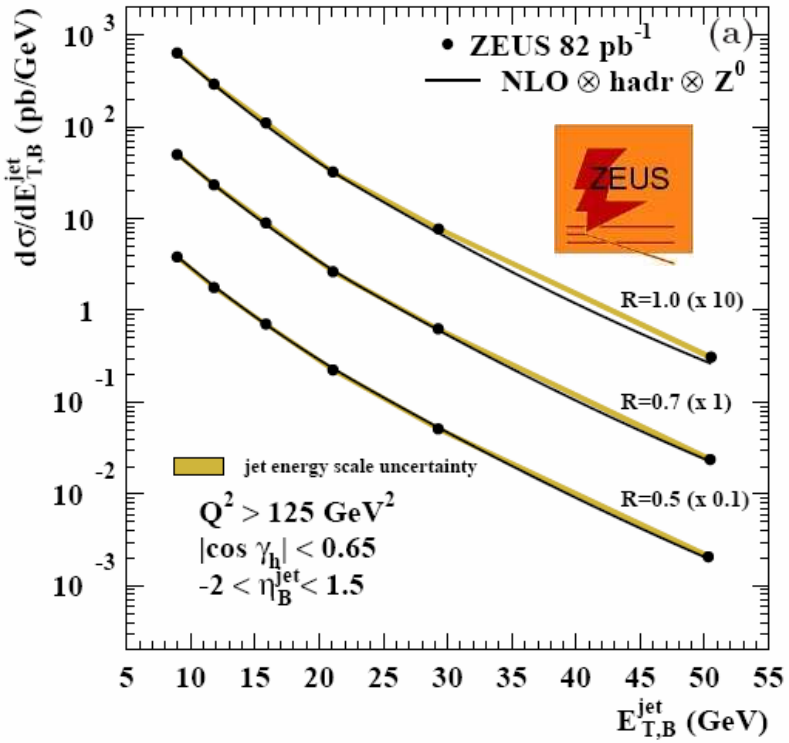
- $L = 65\ pb^{-1}$
  - $150 < Q^2 < 15000\ GeV^2$; $0.2 < y < 0.7$
  - $7 < E_{T,B}^{JET} < 50\ GeV$; $-1 < \eta_{LAB}^{JET} < 2.5$
- Small experimental uncertainties ~ 5%
- Parton-to-hadron corrections ~ 10%
- Good description by NLO QCD
  - $\mu_R = E_{T,B}^{JET}$, $\mu_F = Q$
  - CTEQ6.5 PDFs

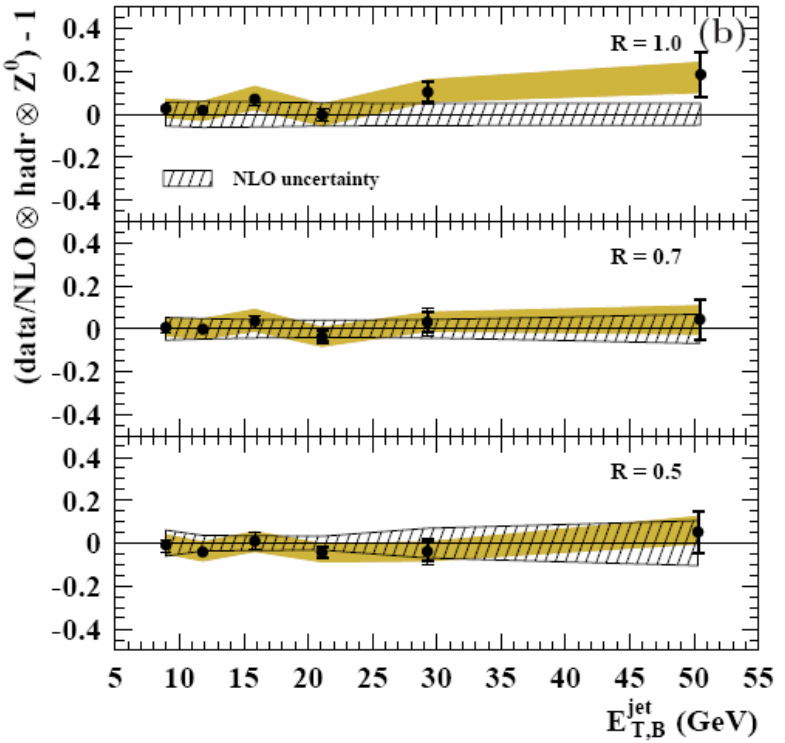


Jet Radius

- $L = 82\ pb^{-1}$
  - $Q^2 > 125\ GeV^2$; $|\cos\gamma| < 0.65$
  - $E_{T,B}^{JET} > 8\ GeV$; $-2 < \eta_B^{JET} < 1.5$
- 3 different radius-like parameter of the k_T algorithm
  - R (= D) = 0.5, 0.7 and 1.0
- Small theoretical and experimental uncertainties
  - Jet Energy Scale (1% for $E_{T,B}^{JET} > 10\ GeV$)
    - ⇨ ~ 5% on the cross sections
  - Parton-to-hadron corrections < 10%
- Good description by NLO QCD
  - $\mu_R = E_{T,B}^{JET}$, $\mu_F = Q$ and ZEUS-S PDFs

Phys. Lett. B 649, 12 (2007)



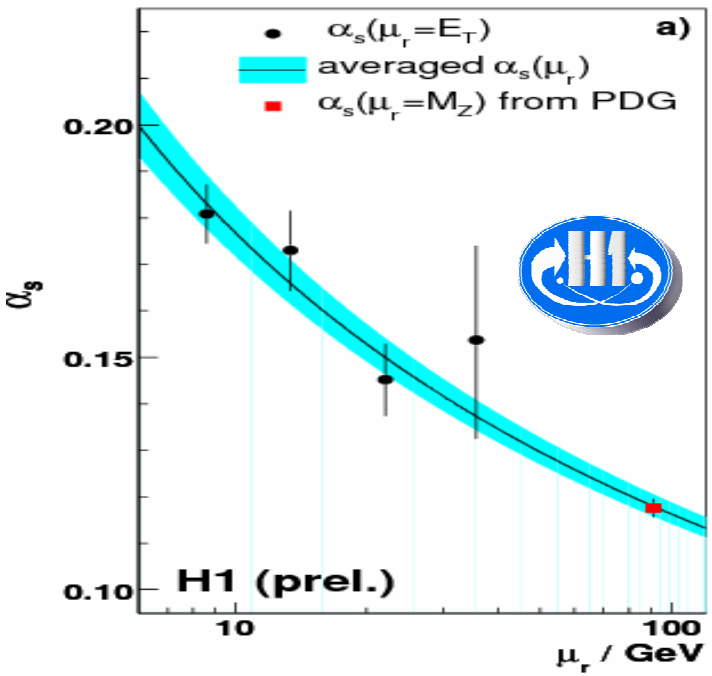


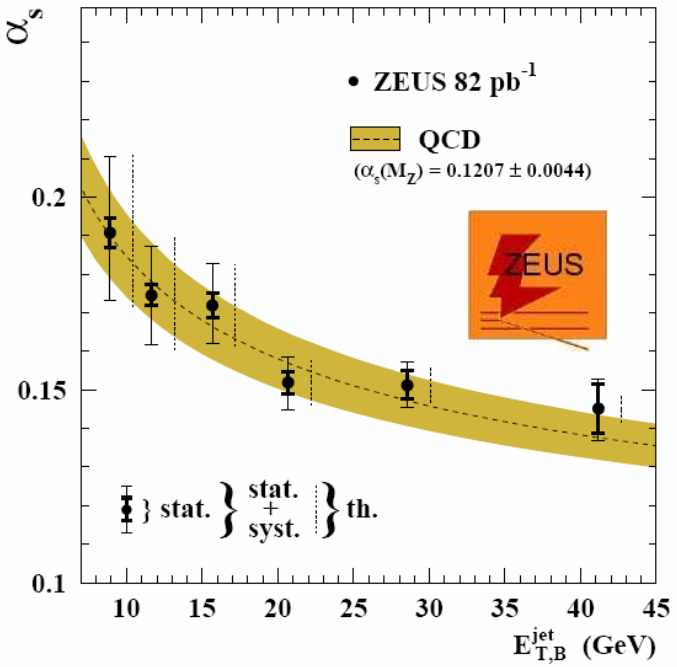
Inclusive Jet Production in NC DIS and α_S

- Previous results used to extract α_S
  - H1
    - $\alpha_S\,(M_Z) = 0.1179 \pm 0.0024$ (exp.) $+0.0052/-0.0032$ (th.) ± 0.0030 (pdf)
      - Using normalised inclusive jet cross section ($\sigma_{JETS} / \sigma_{NCDIS}$) experimental and PDF uncertainties are reduced
    - $\alpha_S\,(M_Z) = 0.1193 \pm 0.0014$ (exp.) $+0.0046/-0.0032$ (th.) ± 0.0016 (pdf)
  - ZEUS
    - $\alpha_S\,(M_Z) = 0.1207 \pm 0.0014$ (stat.) $+0.0035/-0.0033$ (exp.) $+0.0022/-0.0023$ (th.)

⇨ Precise determinations of $\alpha_S\,(M_Z)$
  - Consistent with world average

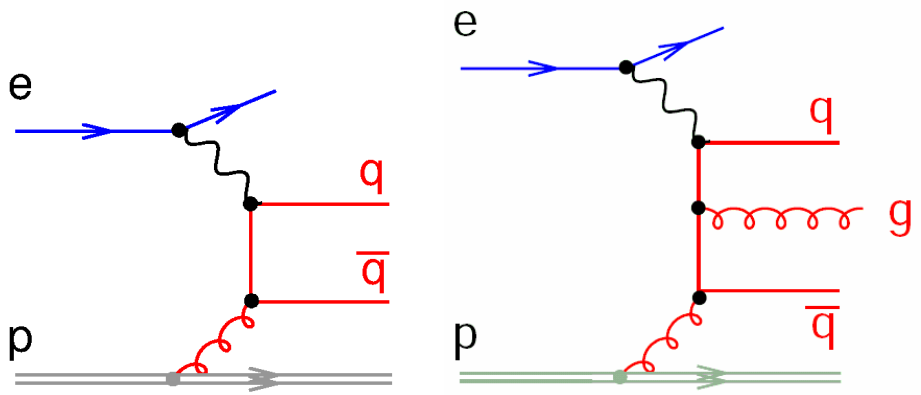
\+ Demonstrations of the running of α_S





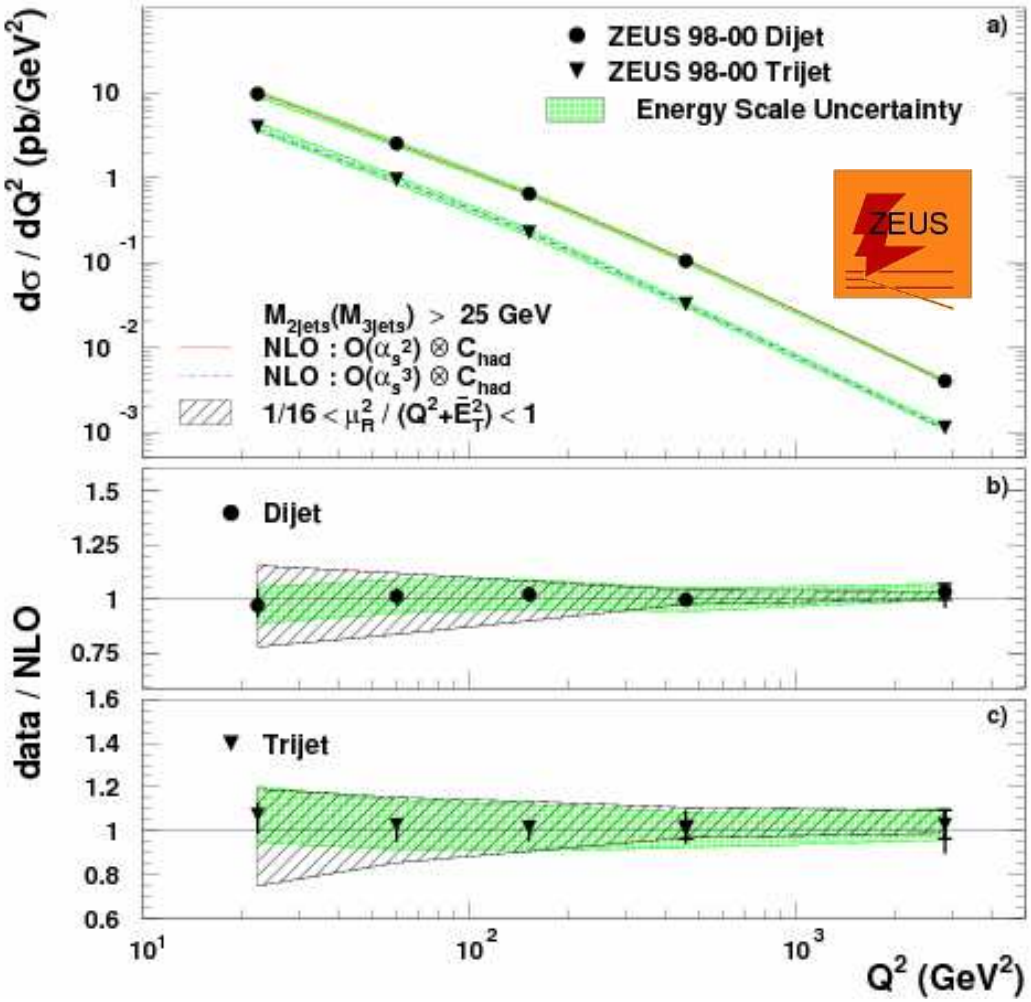
Multijets at High Q^2

- α_S from 3-jet / 2-jet ratio
  - ☺ Partial cancellation of uncertainties (e.g. on gluon density)
  - ☹ But less statistics



- ZEUS: L = 82 pb^{-1}
  - M_{2JET}, M_{3JET} > 25 GeV
  - $10 < Q^2 < 5000$ GeV^2 ; $0.04 < y < 0.6$
  - $-1 < \eta_{LAB}^{JET} < 2.5$

⇨ Good description by NLO QCD (CTEQ6 PDFs)

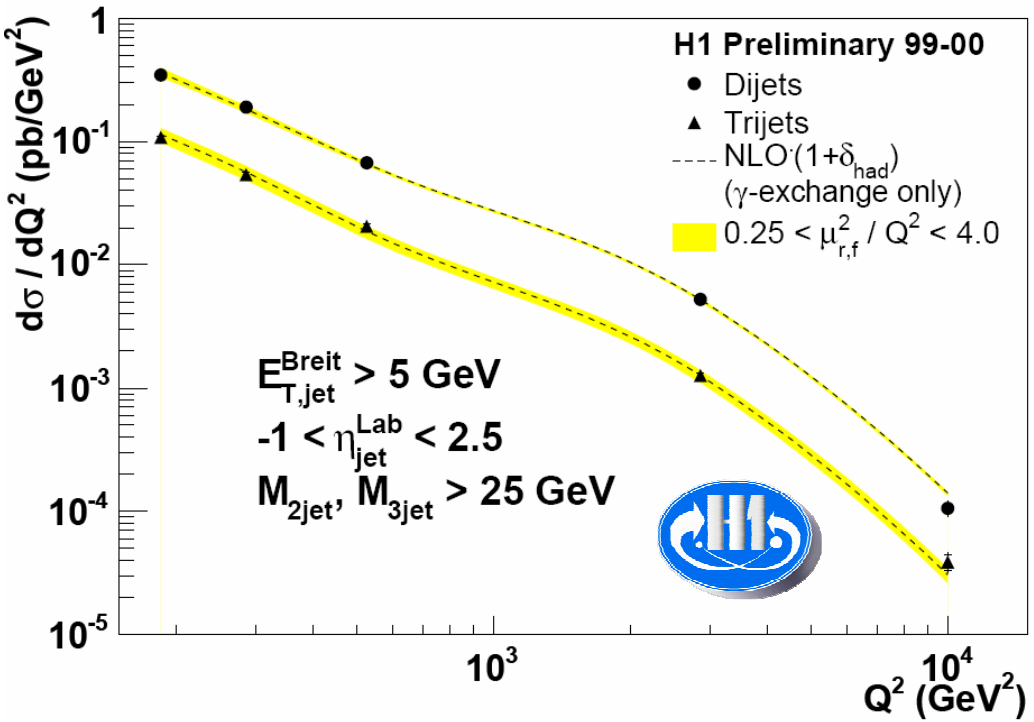


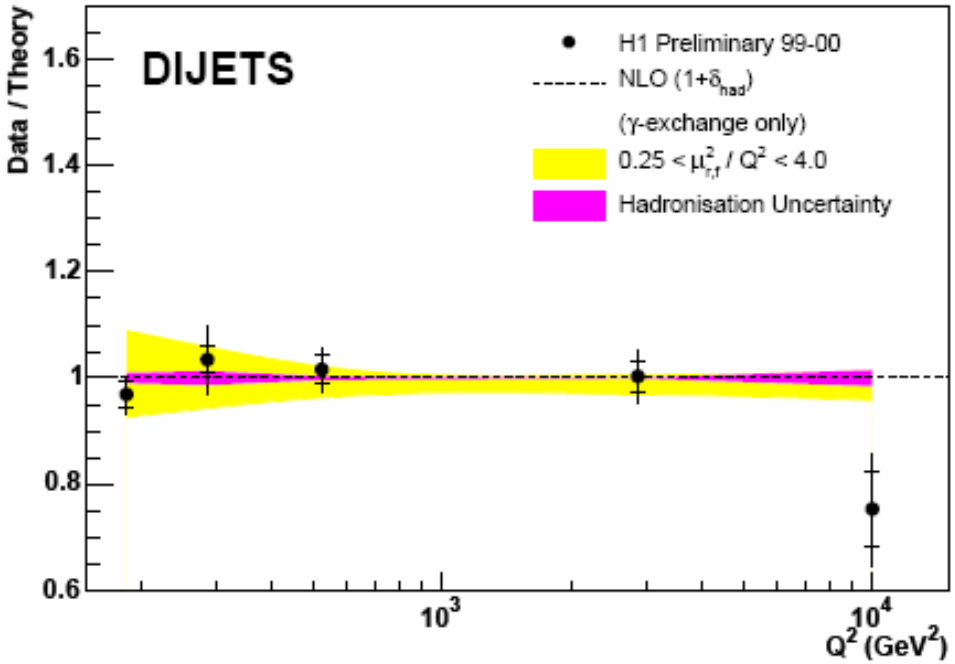
Eur. Phys. J. C44, 183 (2005)

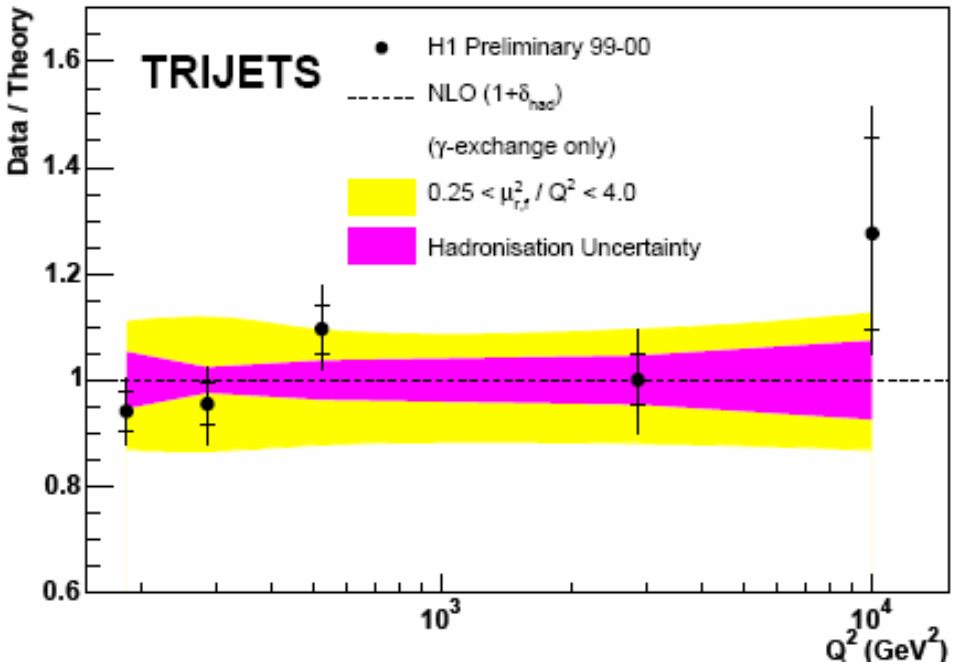
Multijets at High Q^2

- H1: L = 65 pb^{-1}
  - M_{2JET}, M_{3JET} > 25 GeV
  - $125 < Q^2 < 15000$ GeV^2 ; $0.2 < y < 0.6$
  - $E_{T,B}^{JET} > 5$ GeV ; $-1 < \eta_{LAB}^{JET} < 2.5$

⇨ Good description by NLO QCD (CTEQ4A PDFs)

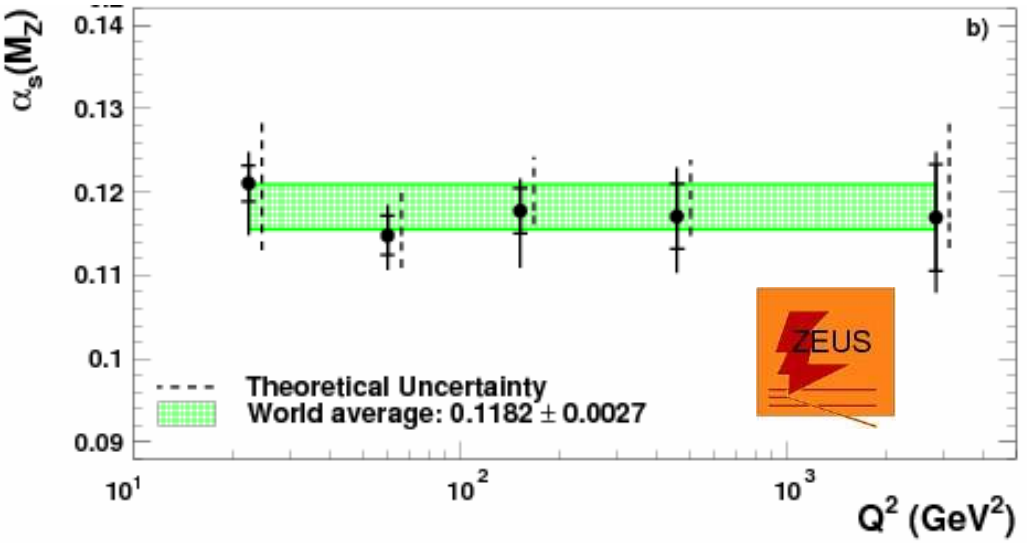




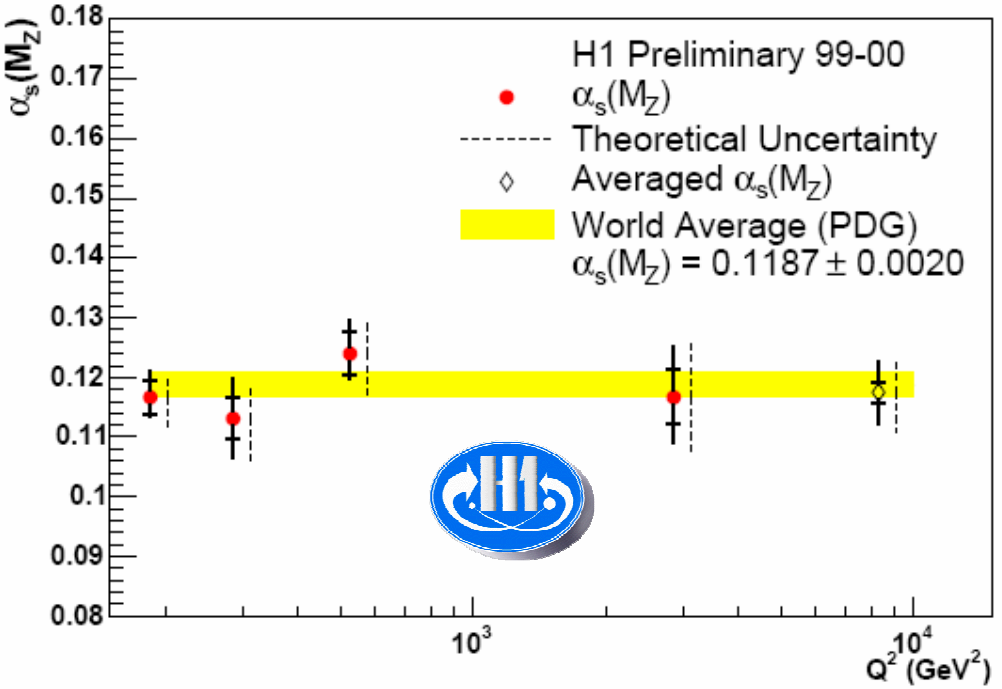


α_S from multijets

- ZEUS
  - $\alpha_S\,(M_Z) = 0.1179 \pm 0.0013$ (stat.)
    +0.0028/-0.0046 (exp.)
    +0.0064/-0.0046 (th.)

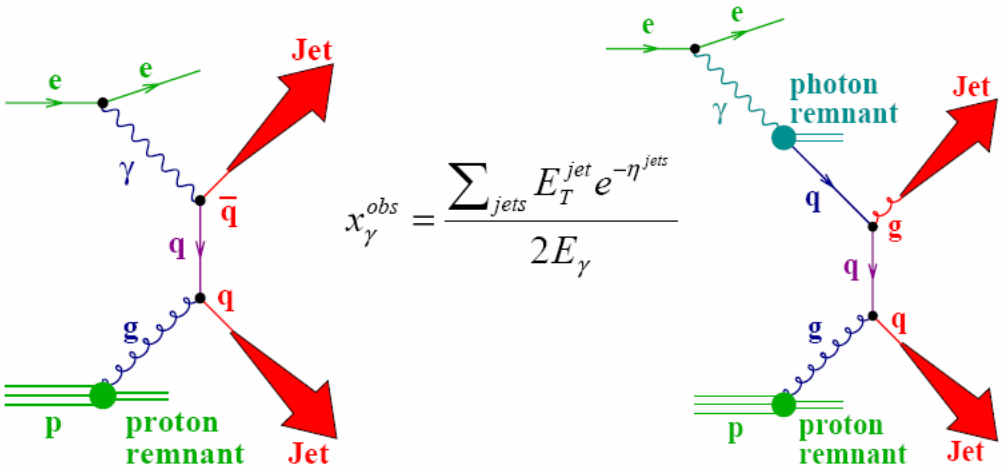


- H1
  - $\alpha_S\,(M_Z) = 0.1175 \pm 0.0017$ (stat.)
    $\pm$ 0.0050 (exp.) +0.0054/-0.0068 (th.)



Inclusive Jets in γp

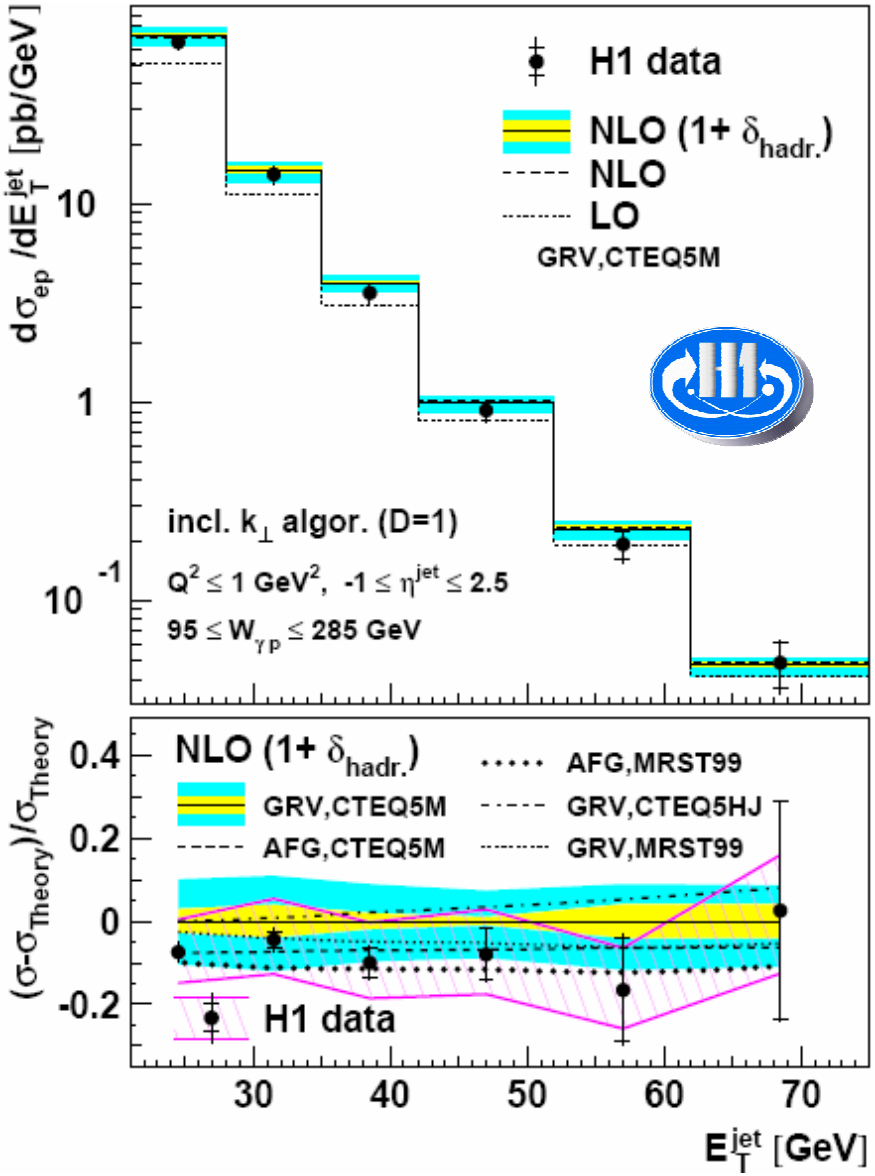
- Photo-production: quasi real photons
  - Scattered electron stays in beam pipe



$$x_\gamma^{obs} = \frac{\sum_{jets} E_T^{jet} e^{-\eta^{jets}}}{2E_\gamma}$$

direct ($x_\gamma^{obs} > 0.75$) resolved ($x_\gamma^{obs} < 0.75$)

  - Resolved γp similar to hadron-hadron
  - Large σ: access to high E_T^{JET}
- H1 data: L = 24 pb^{-1}
  - $Q^2 < 1GeV^2$; $95 < W_{\gamma p} < 285$ GeV
    - $W_{\gamma p}$ = γp center of mass energy
  - $5 < E_T^{JET} < 75$ GeV ; $-1 < \eta^{JET} < 2.5$



Eur. Phys. J. C29, 497 (2003)

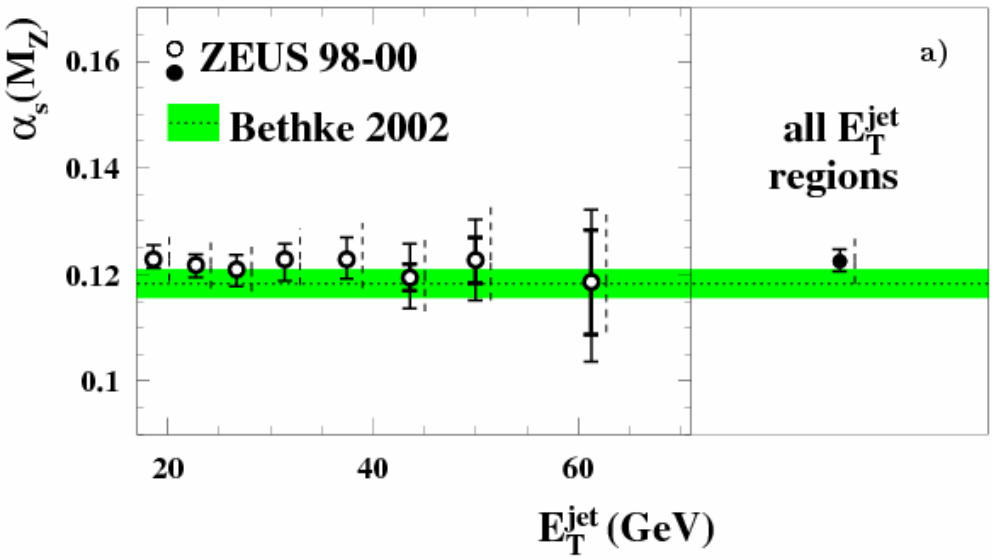
Inclusive Jets in γp and α_s

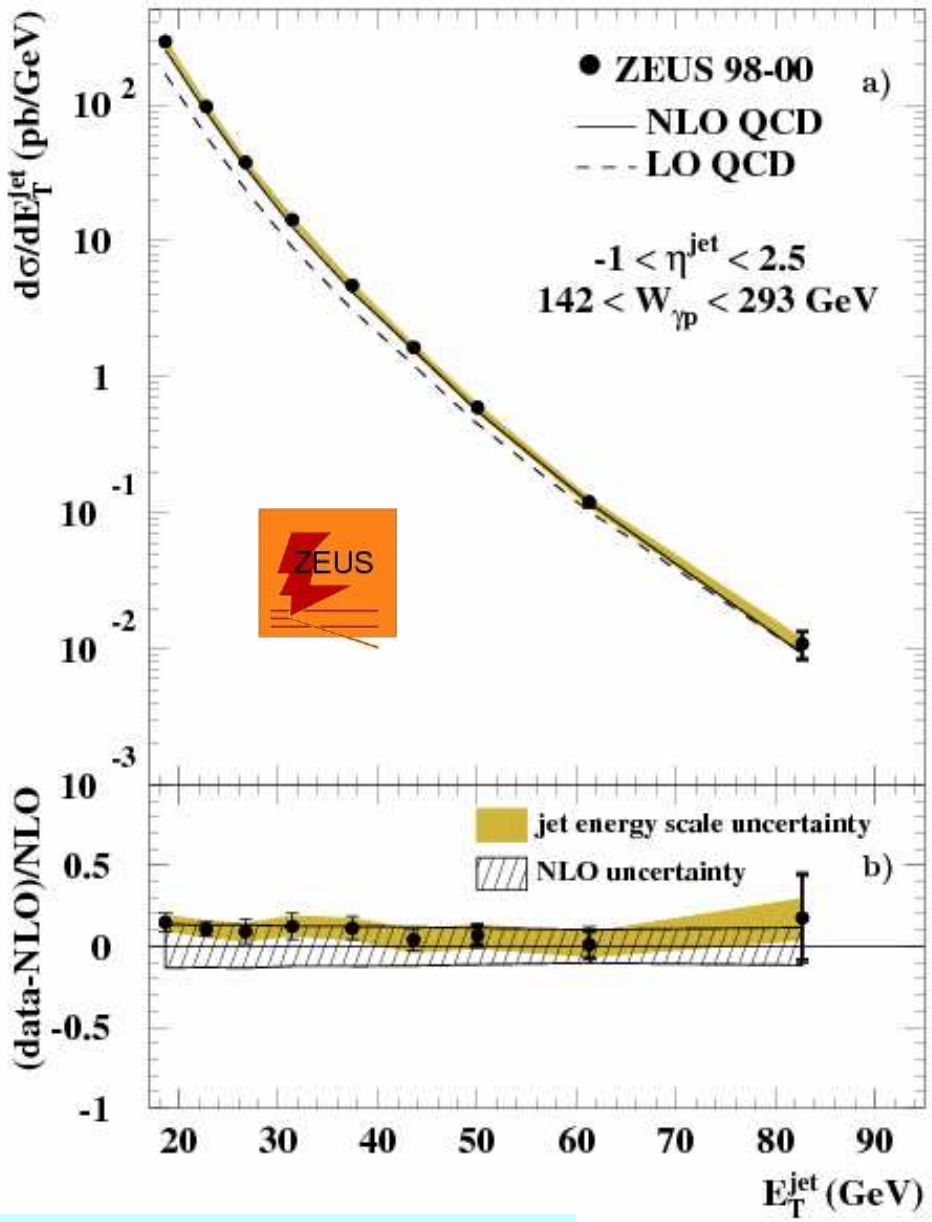
ZEUS data: L = 82 pb^{-1}

- $142 < W_{\gamma p} < 293$ GeV
- $17 < E_T^{JET} < 95$ GeV ; $-1 < \eta^{JET} < 2.5$

⇨ $$\alpha_s(M_Z) = 0.1224 \pm 0.0001\ (\text{stat.})\ ^{+0.0022}_{-0.0019}\ (\text{exp.})\ ^{+0.0054}_{-0.0042}\ (\text{th.})$$

⇨ Consistent with NC DIS (different process!)

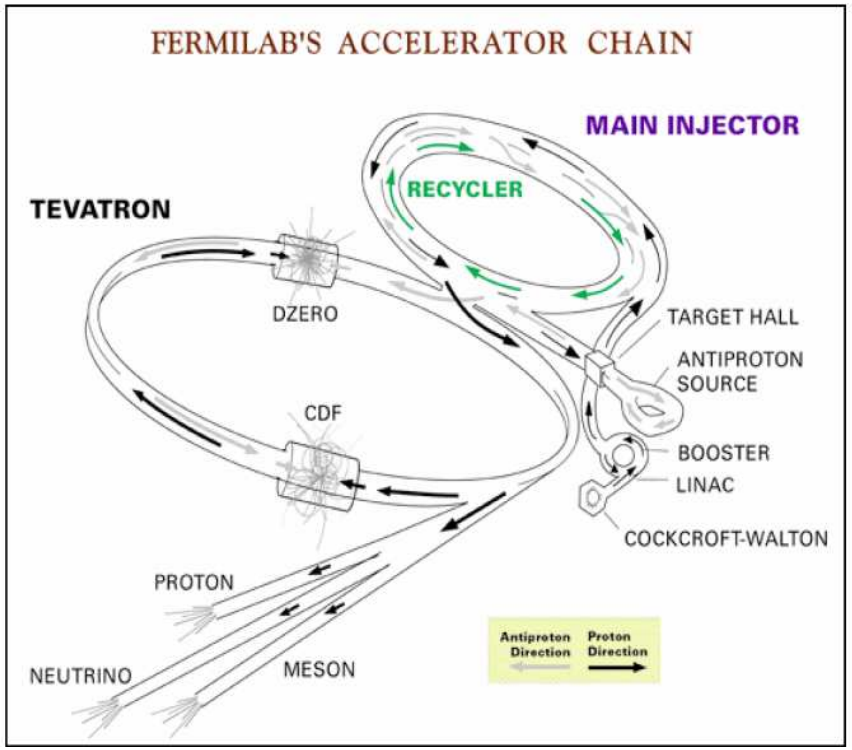


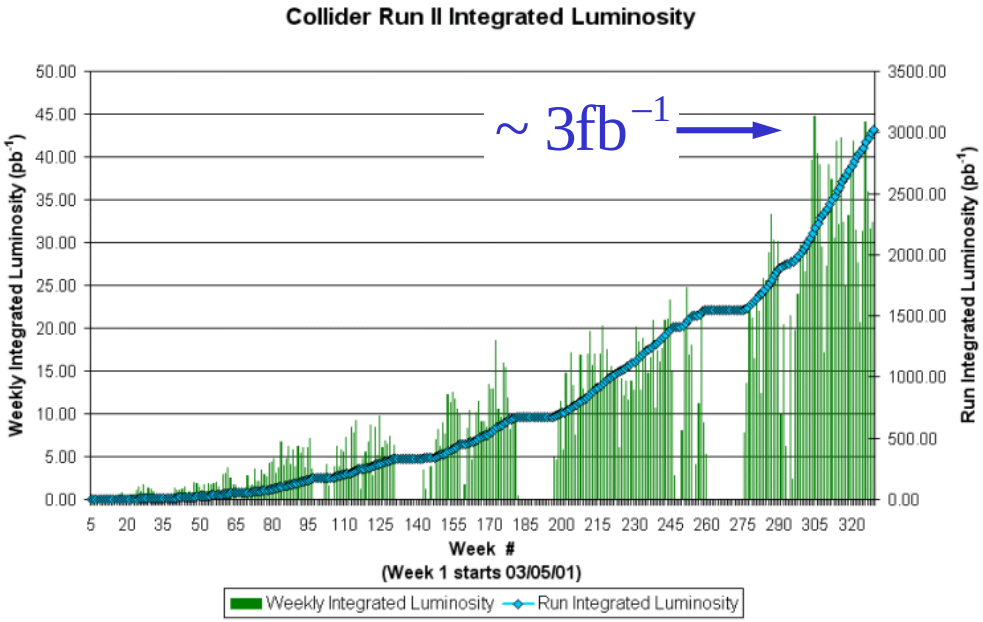


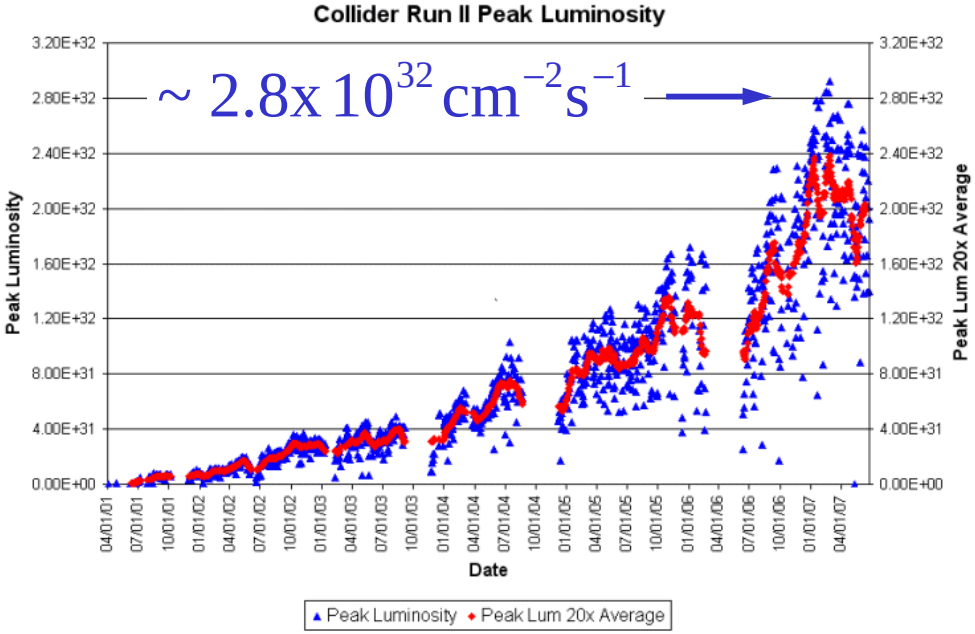
Phys. Lett. B560, 7 (2003)

The Tevatron

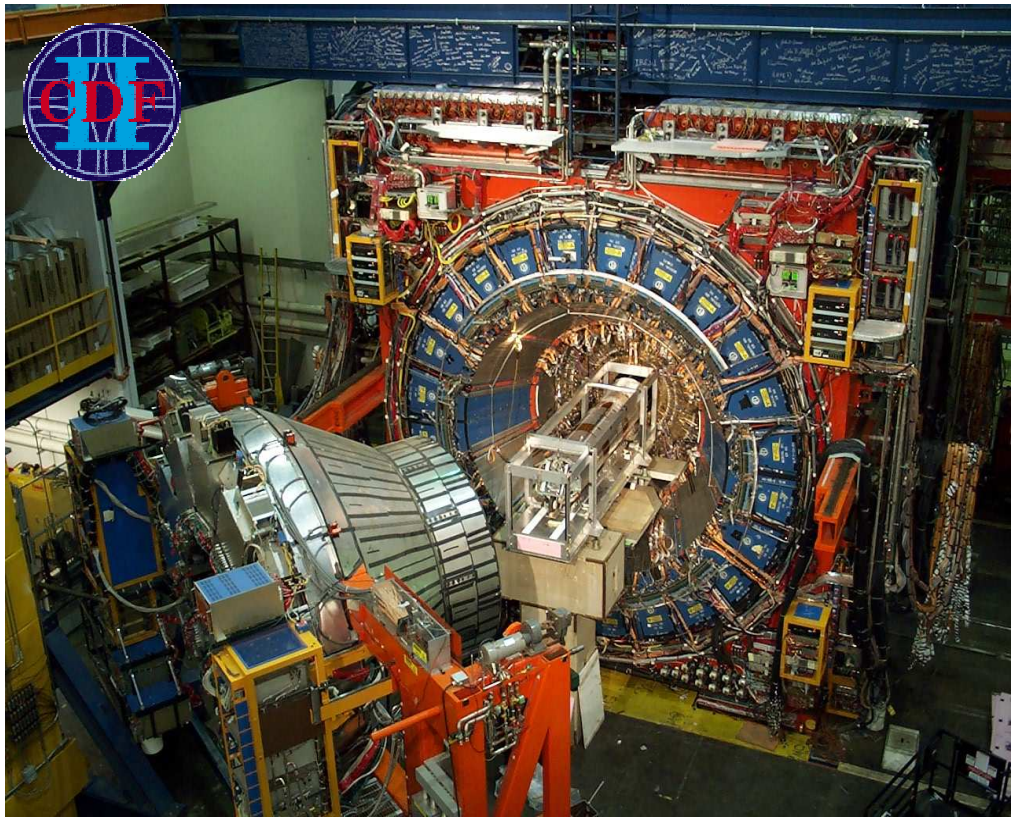
- Proton-antiproton collisions
- $\sqrt{s}$ = 1.96 TeV
- 36 bunches: crossing time = 396 ns
- ☺ Delivered ~ 1.5 fb-1 since 06/2006
- Current extrapolation ~ 6 fb^{-1} by 2009
  - 8 fb^{-1} still the goal
    - Need increased antiproton staking rates







CDF and DØ Detectors

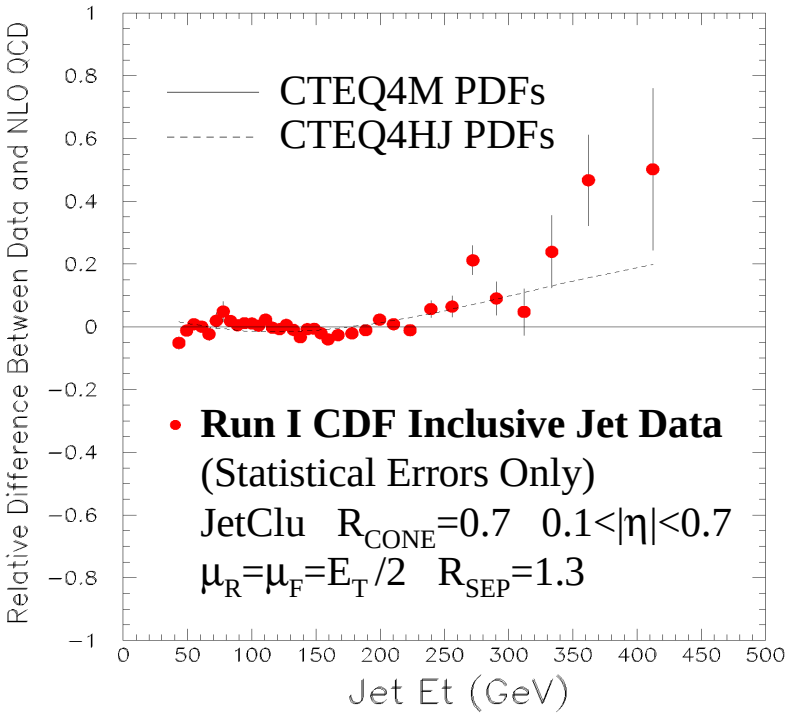


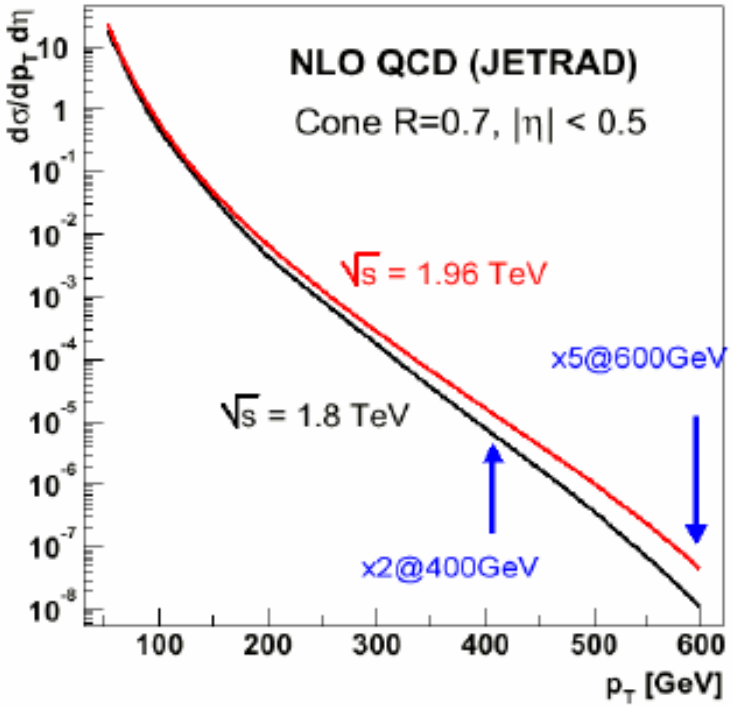
- CDF and DØ operating well
  - Recording physics quality data with very high efficiency (80 to 85 %)

⇨ Both experiments have already collected ~ 2.5 fb^{-1}

Inclusive Jets @ Tevatron

- Legacy from Run I
  - Great interest on apparent excess at high E_T
  - SM explanation
    - Gluon PDF increased at high x
    - Recent PDFs from global fit include CDF and D0 jet data from Run I (CTEQ6, MRST2001)

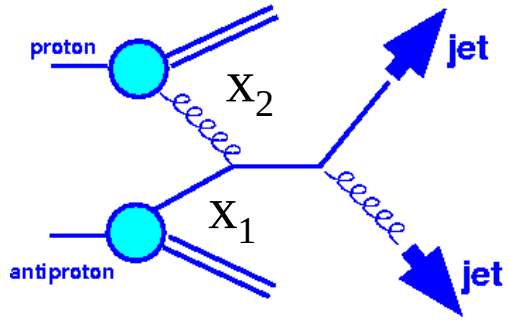


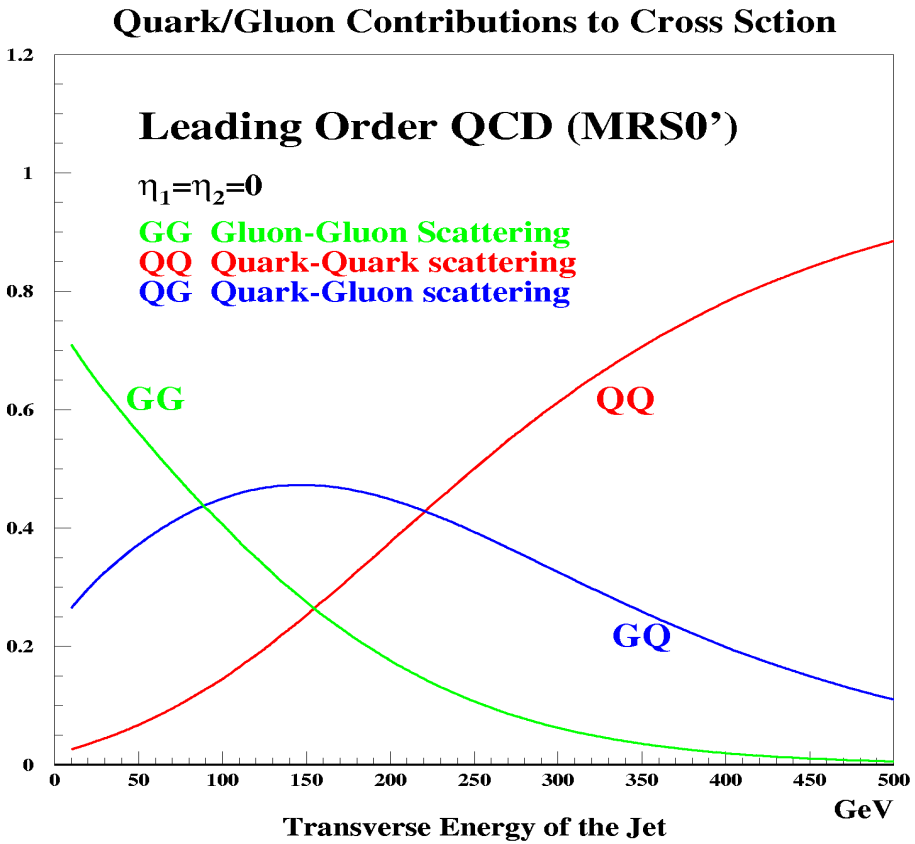


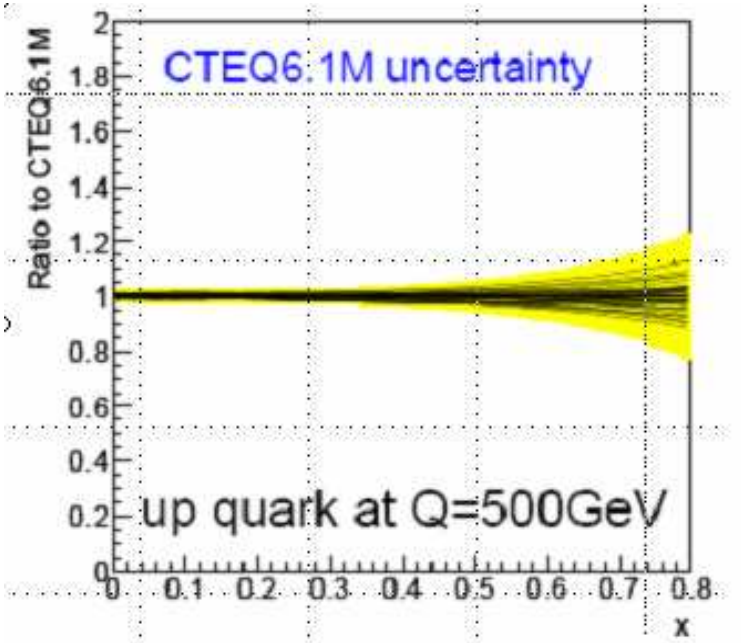
- Stringent test of pQCD
  - Over ~ 8 orders of magnitude
- Tail sensitive to New Physics
  - Probing distances ~ 10^{-19} m
  - Production enhanced at high p_T thanks to new $\sqrt{s}$
- PDFs at high Q^2 & high x

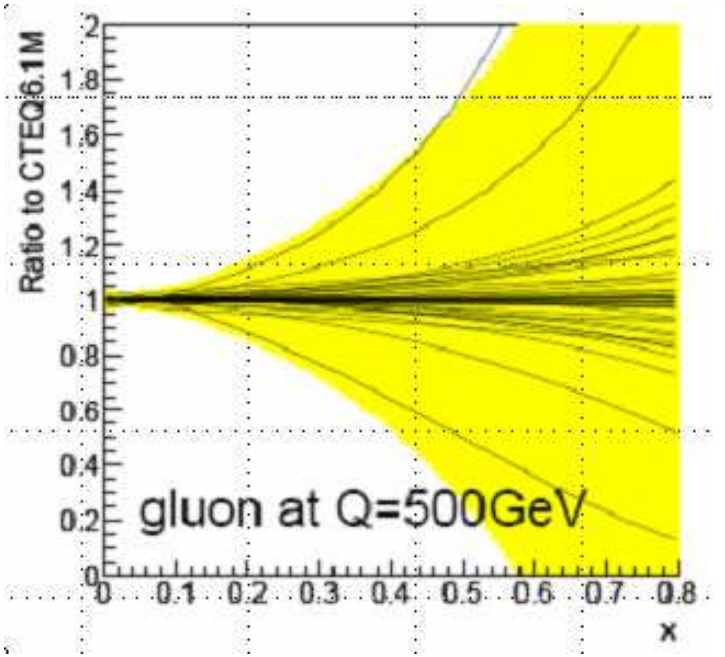
Gluon PDF at high x

$$\sigma_{GQ}^{total} = \sum \int dx_1 dx_2 f_q(x_1, Q^2) f_g(x_2, Q^2) \hat{\sigma}^{parton}$$





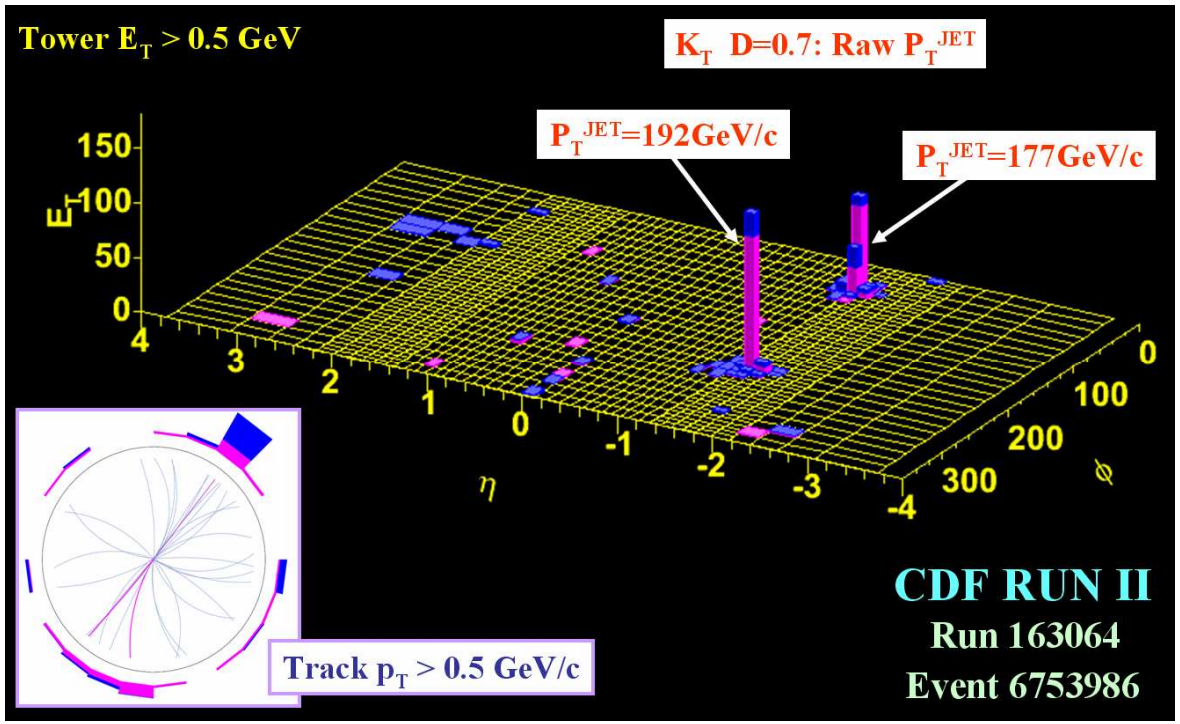


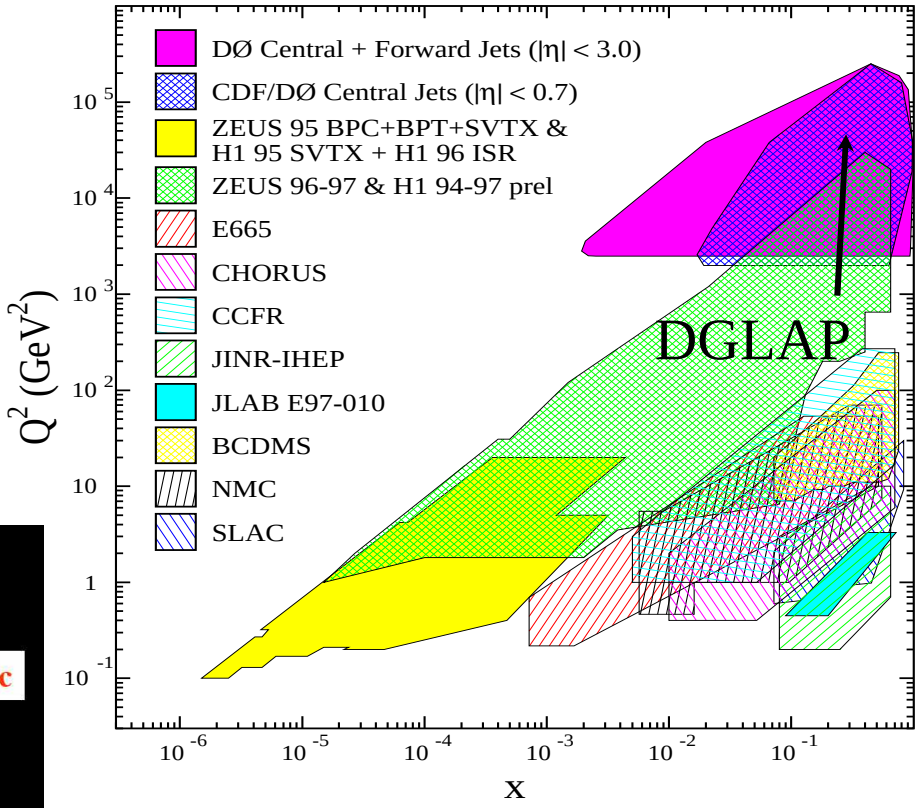


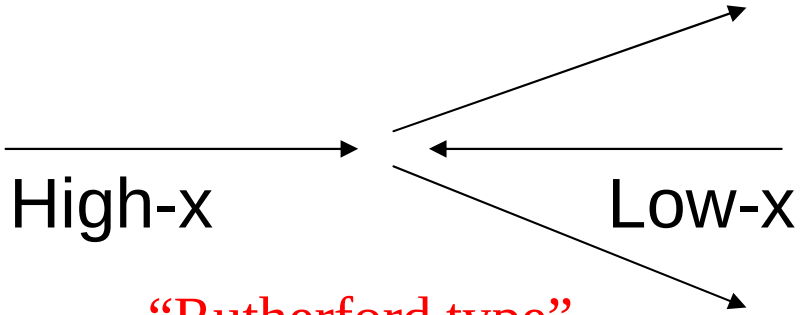
Important GG and GQ contributions

Forward Jets

- Essentials to pin down PDFs vs. eventual New Physics at higher Q^2 in central region
  - DGLAP gives Q^2 evolution
- Expend x range toward low x



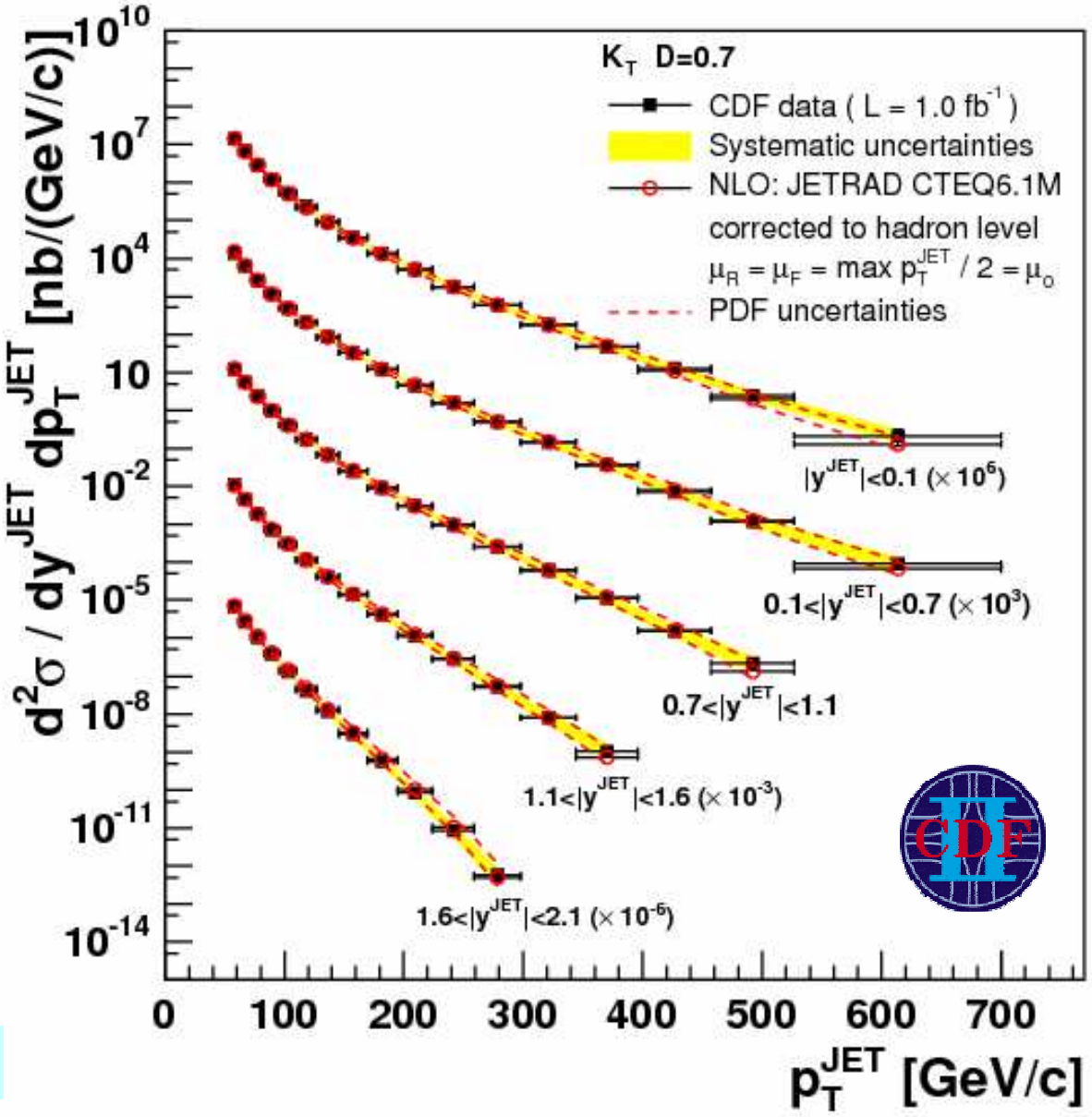




"Rutherford type" parton backscattering

Inclusive Jet Production with k_T

- 5 rapidity ranges
  - Up to $|y^{JET}| = 2.1$
- D = 0.7
- L = 1 fb^{-1}
- Good description by NLO QCD
  - Experimental uncertainties dominated by Jet Energy Scale (2 to 3%)
  - Theoretical uncertainties dominated by PDF (gluon at high x)



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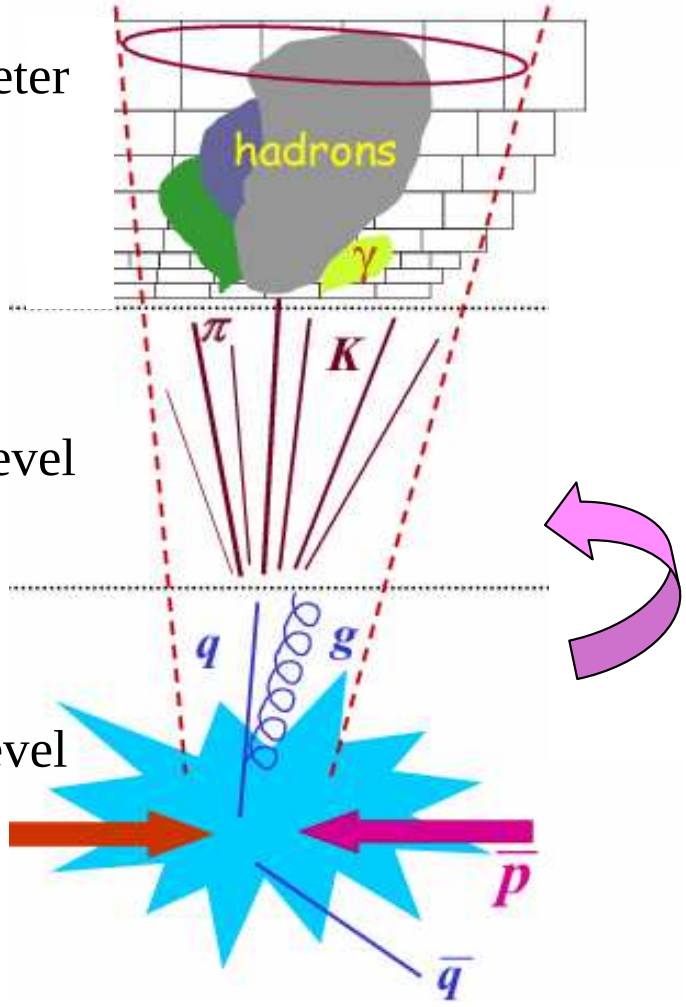
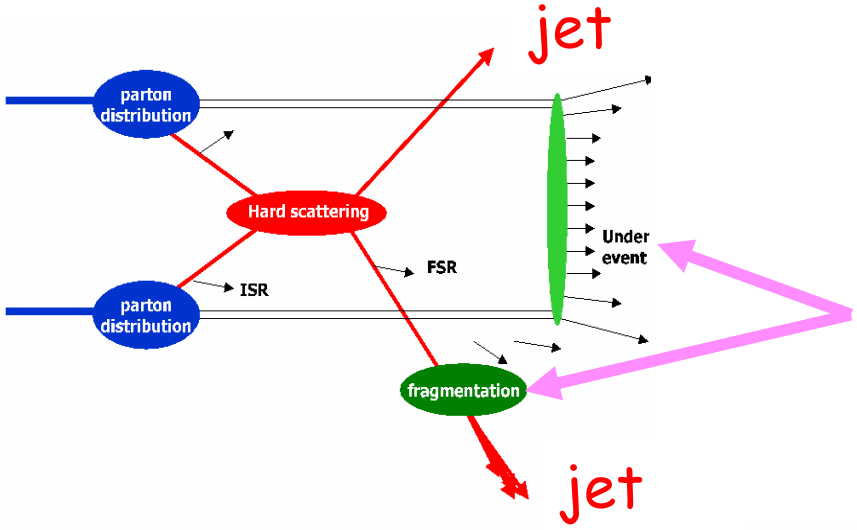
Underlying Event & Hadronization correction

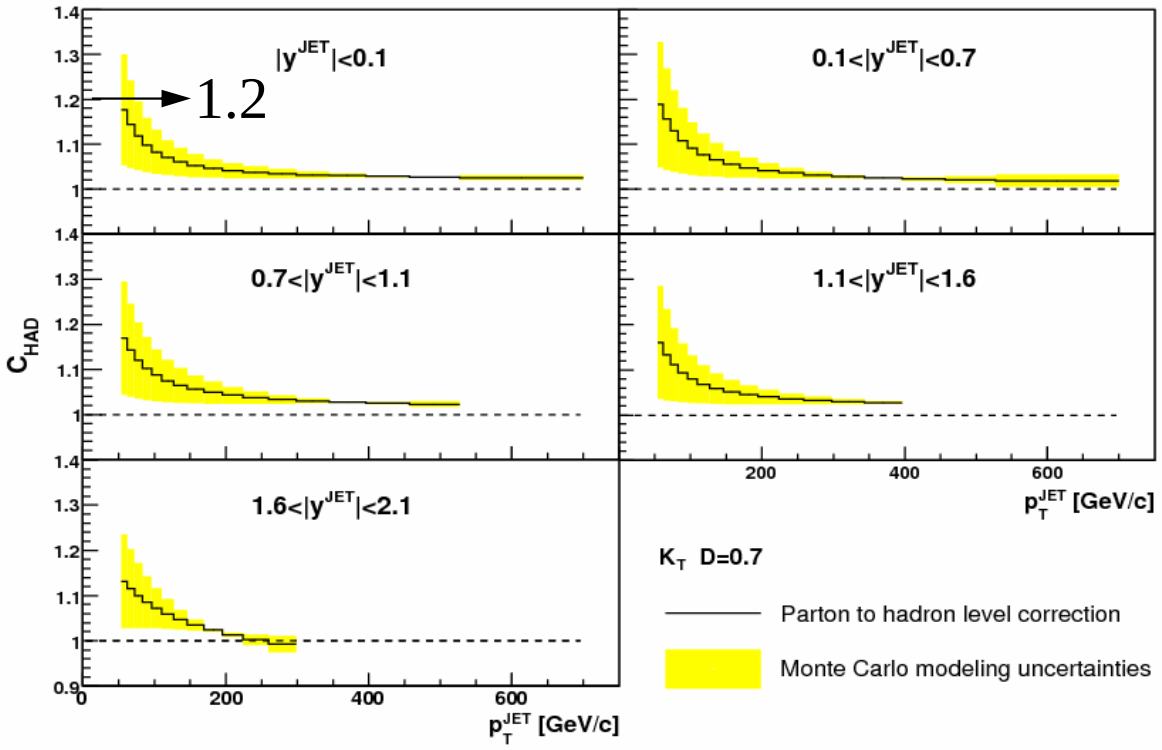
Calorimeter level

Hadron level

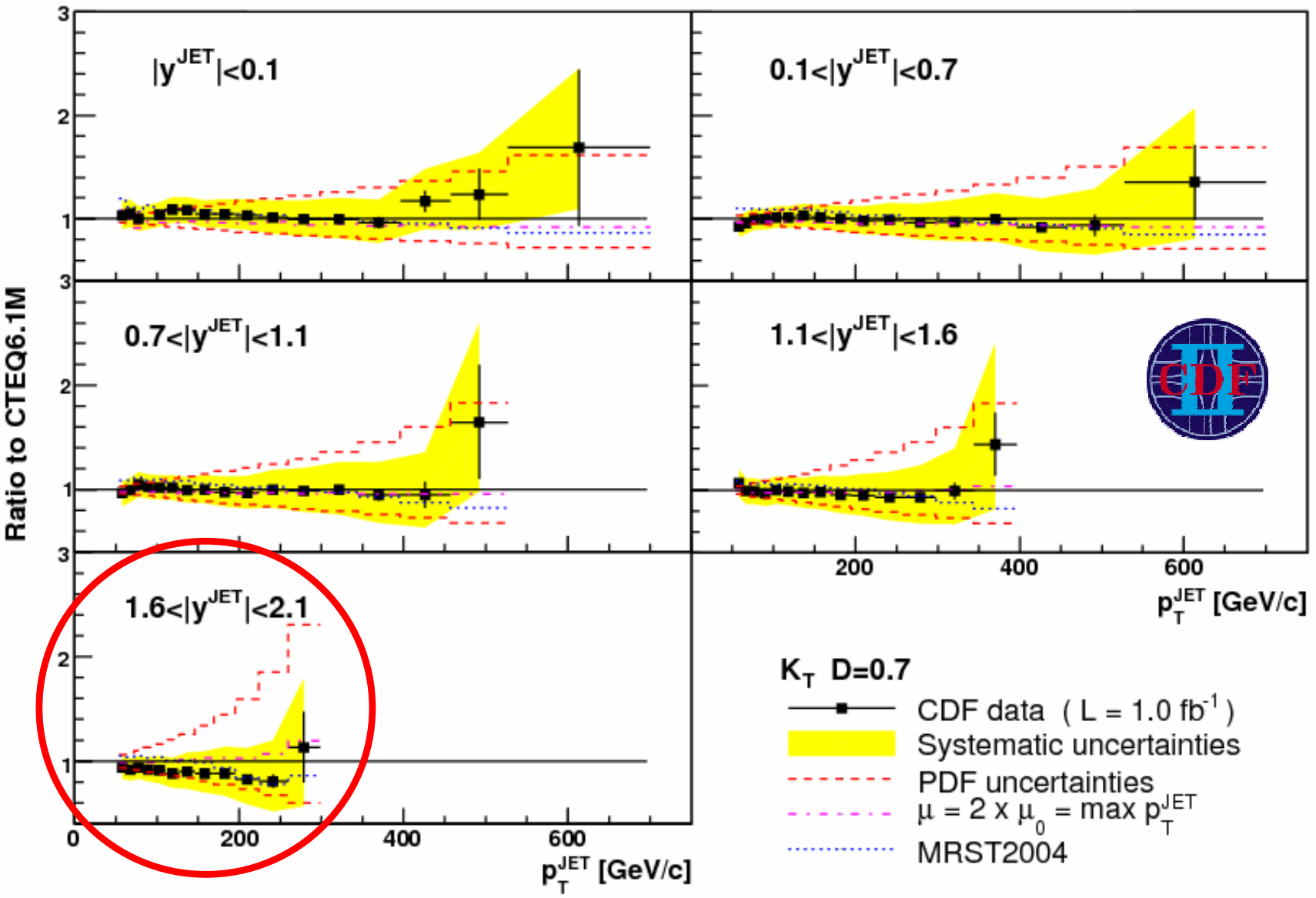
Parton level



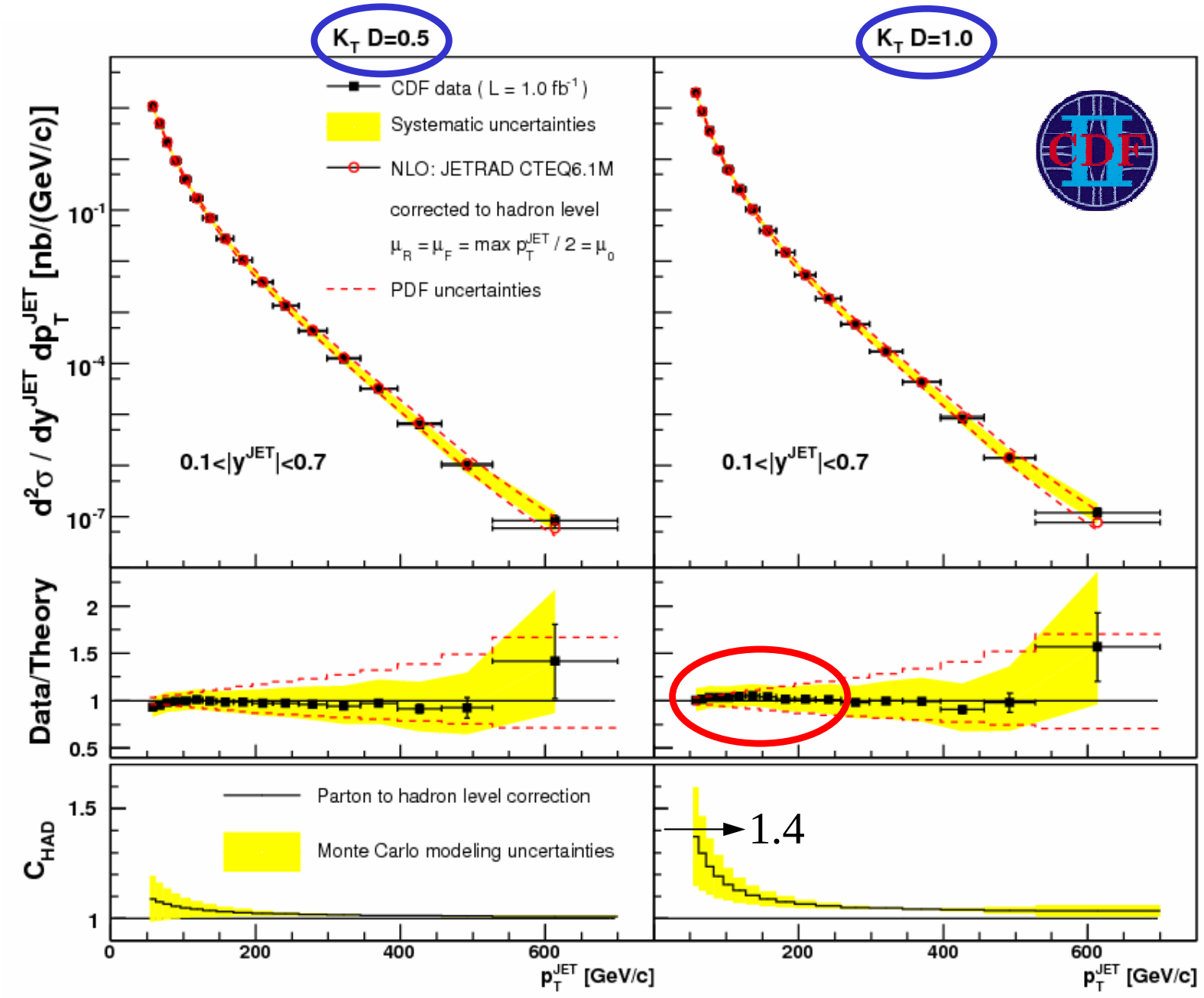




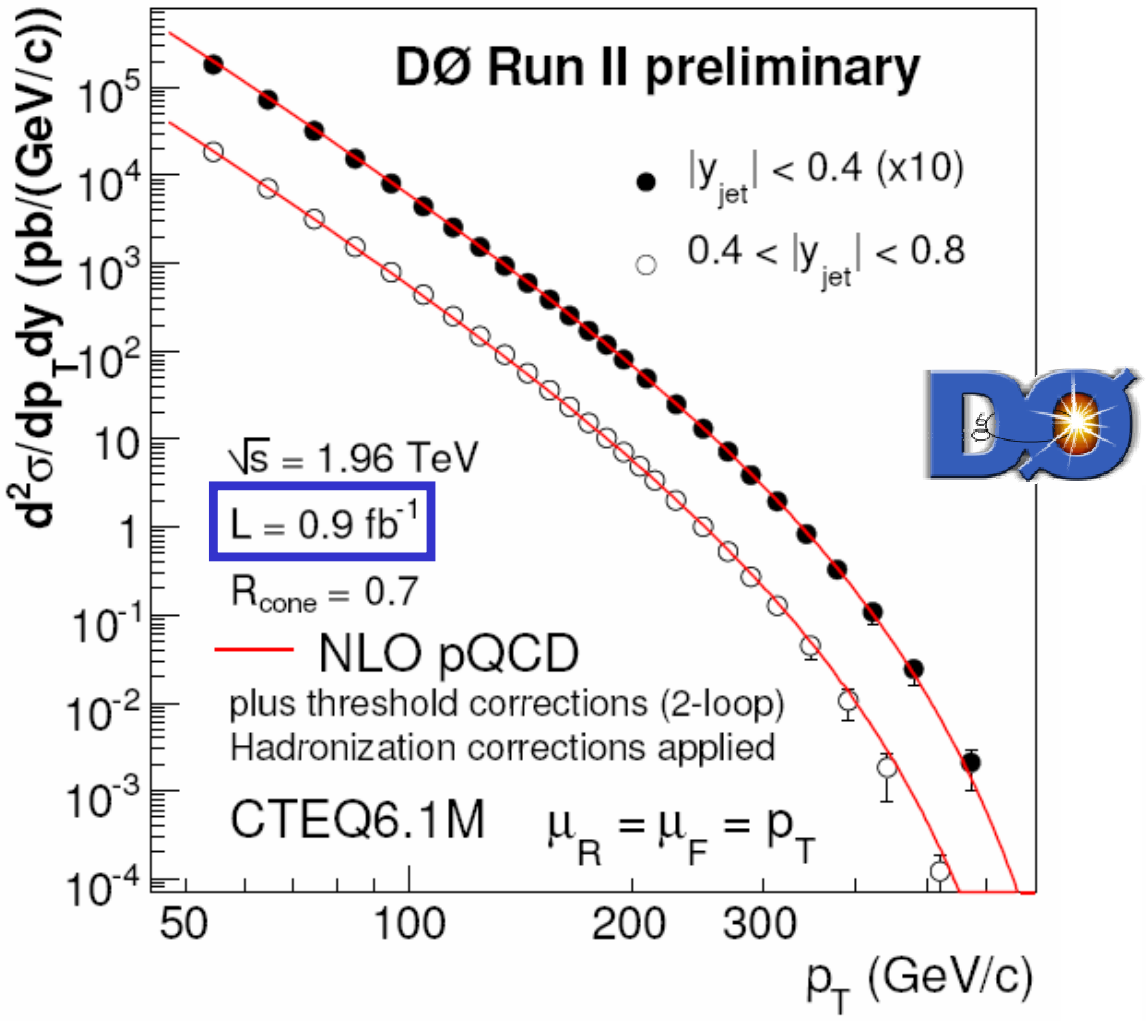
Data / NLO pQCD

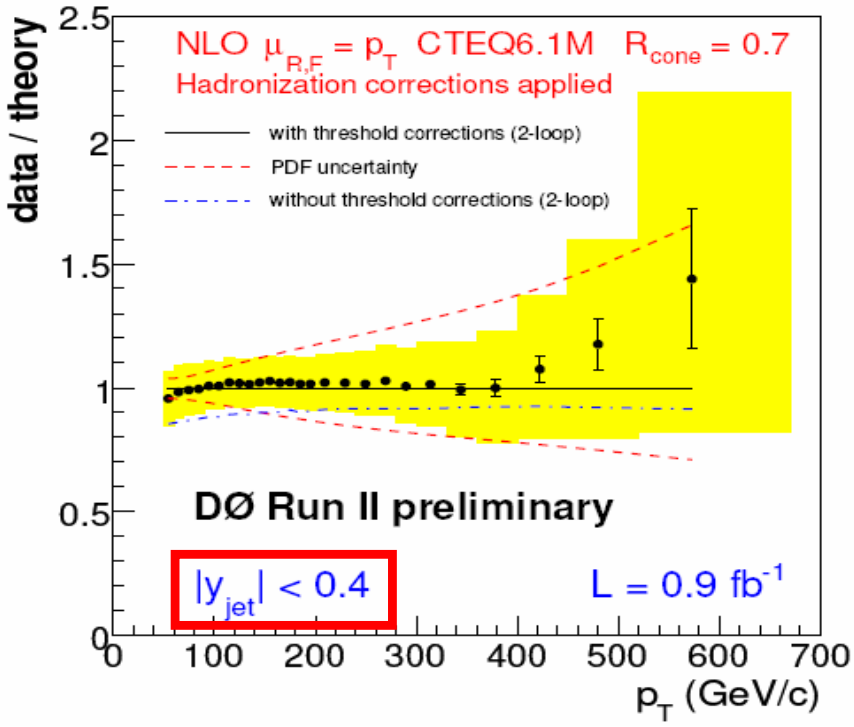


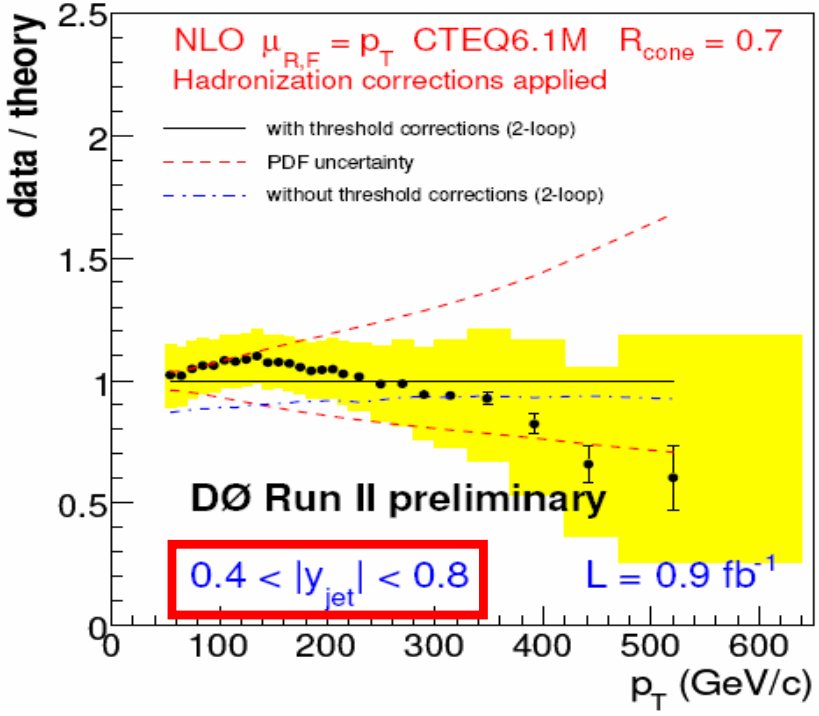
k_T jets vs. D


K_T D=0.5
K_T D=1.0
CDF data (L = 1.0 fb^-1)
Systematic uncertainties
NLO: JETRAD CTEQ6.1M
corrected to hadron level
μ_R = μ_F = max p_T^JET / 2 = μ_0
PDF uncertainties
0.1<|y^JET|<0.7
0.1<|y^JET|<0.7
d²σ / dy^JET dp_T^JET [nb/(GeV/c)]
Data/Theory
C_HAD
Parton to hadron level correction
Monte Carlo modeling uncertainties
1.4
p_T^JET [GeV/c]
p_T^JET [GeV/c]

Inclusive Jet Production with Midpoint



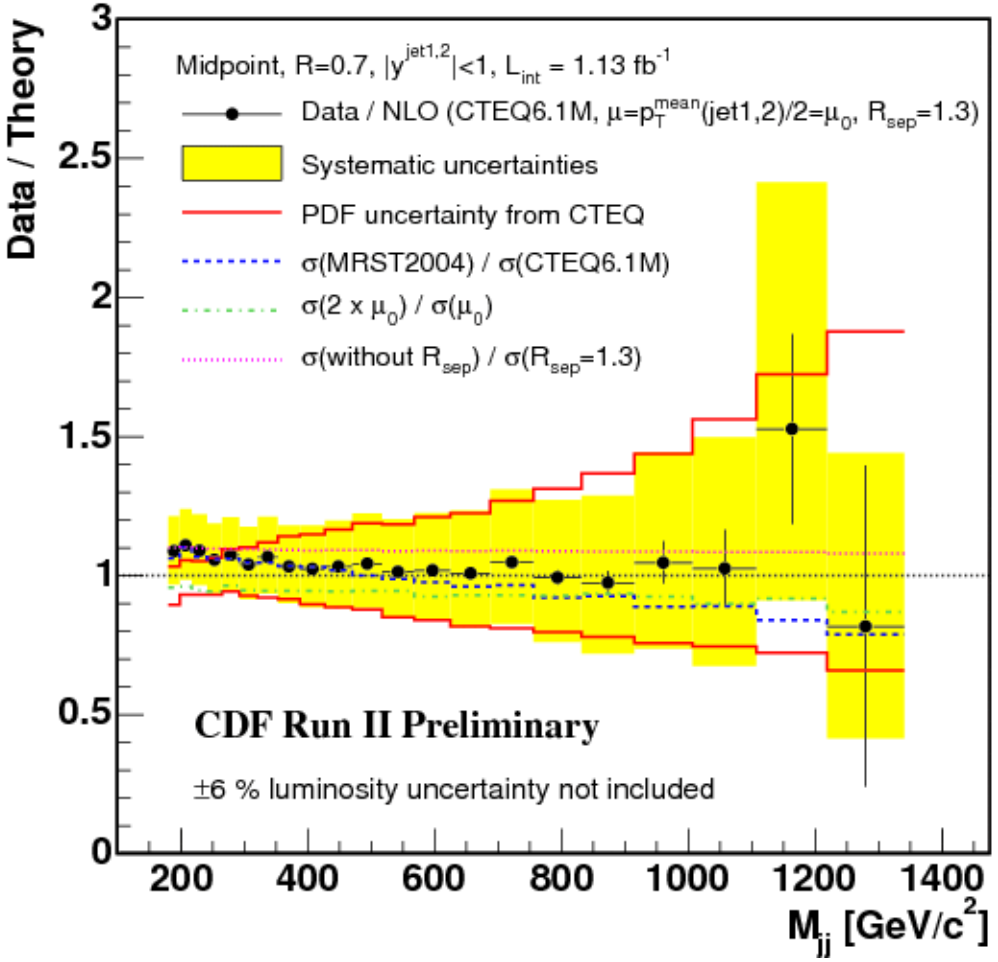


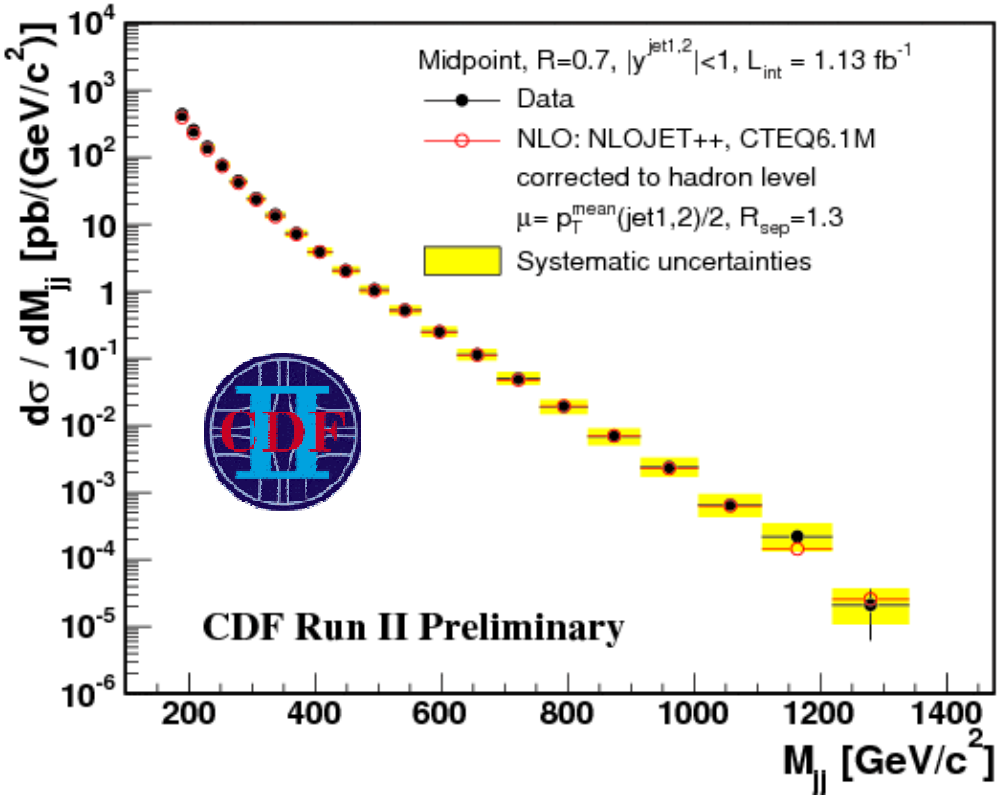


Compared to NLO pQCD + 2-loop Threshold Corrections (N. Kidonakis, J.F. Owens)

Dijet Production

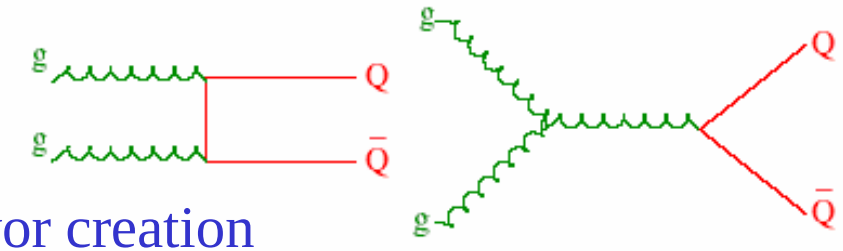
- Midpoint R = 0.7
  - $|y^{JET1,2}| < 1$
  - L = 1.1 fb^{-1}



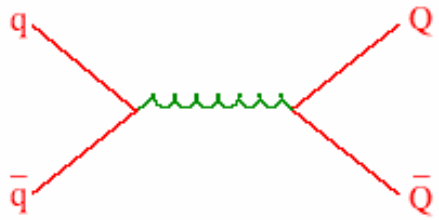


- Consistent with NLO pQCD
  - Experimental uncertainties comparable to PDF ones
- Sensitive to New Physics
  - Heavy resonances, Compositeness
  - Limits being worked out…

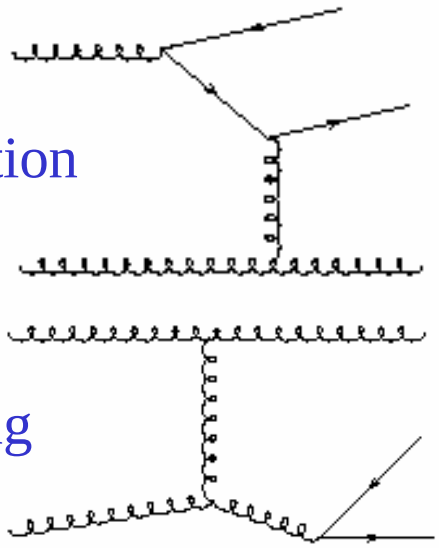
Beauty Production



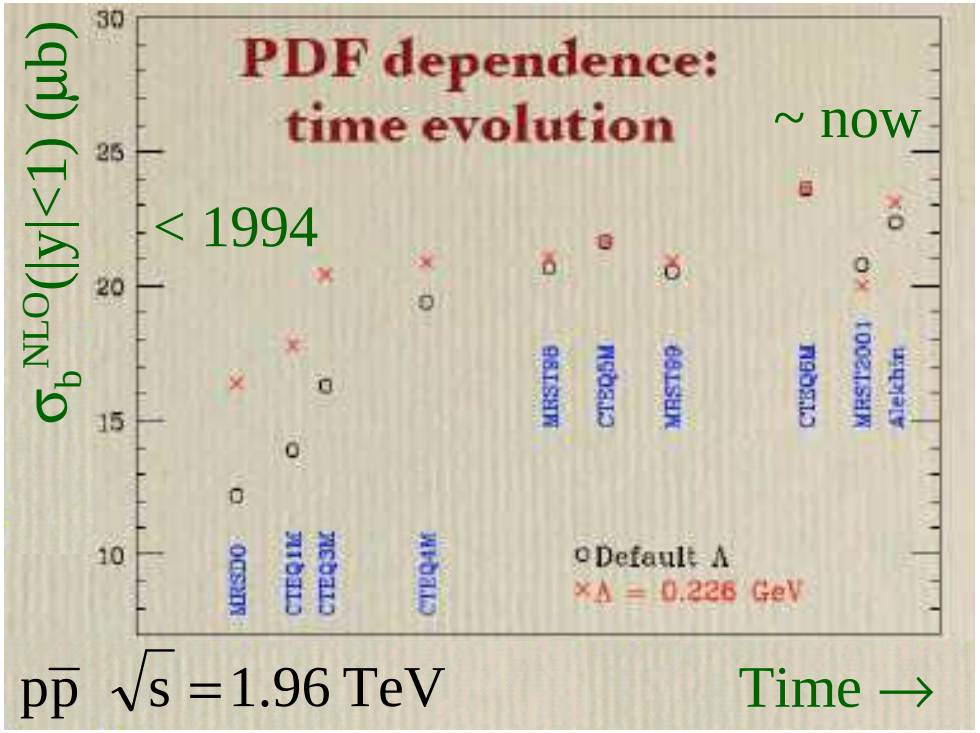
LO: Flavor creation



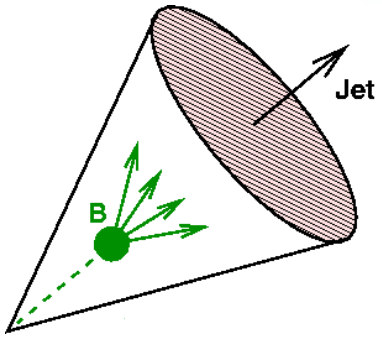
NLO: Flavor excitation

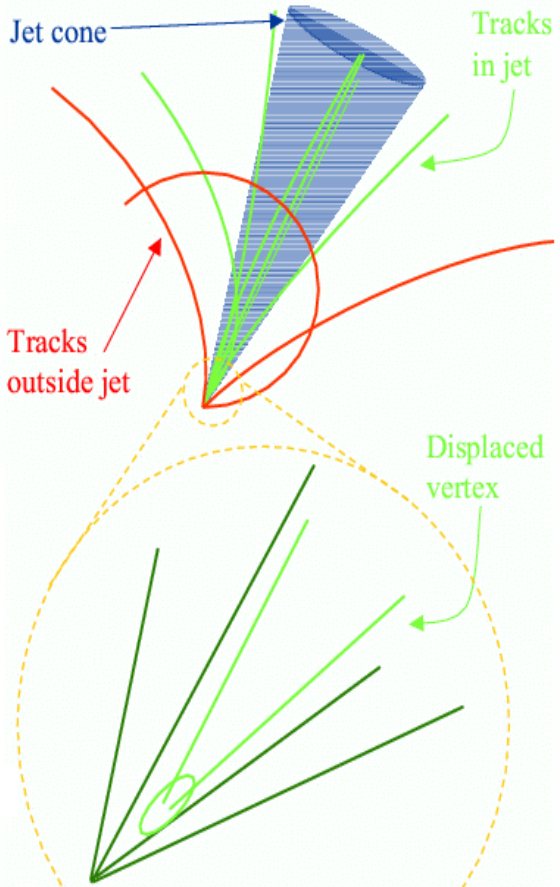


NLO: Gluon splitting



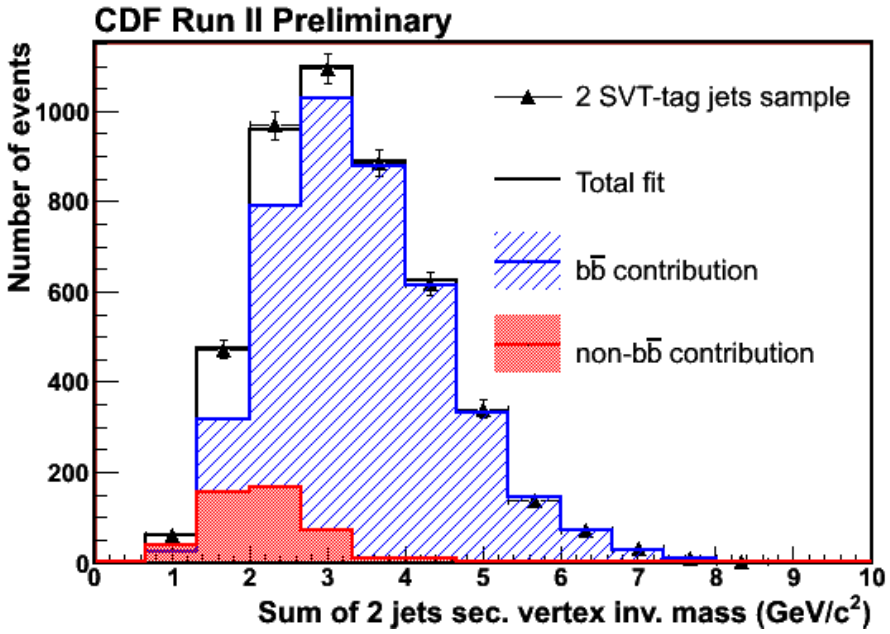
b-tagging based on secondary vertices reconstructed from displaced tracks inside jets



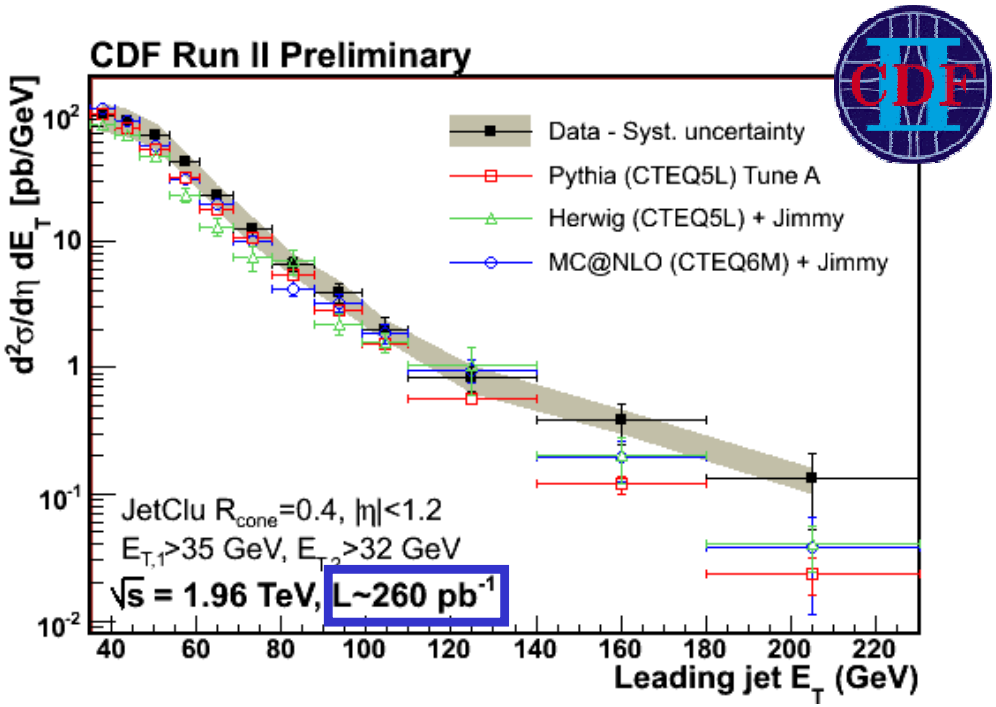


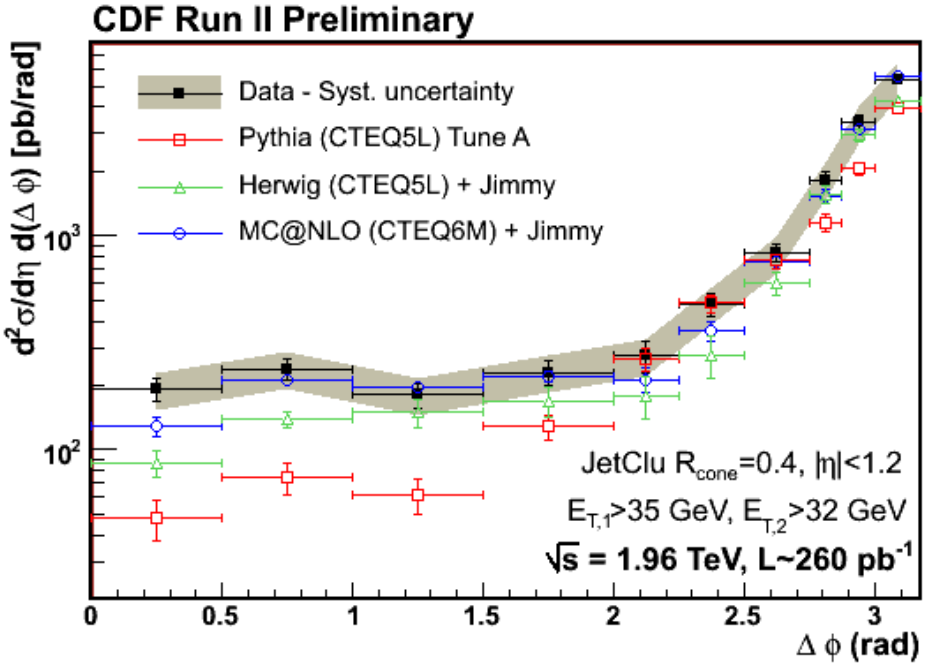
$b\bar{b}$ dijet production

- Sensitive to the different production mechanisms
  - Flavor creation at high $\Delta\phi$
  - Flavor excitation or gluon splitting at low $\Delta\phi$
- SVT (Secondary Vertex Tagging) used at trigger and offline levels



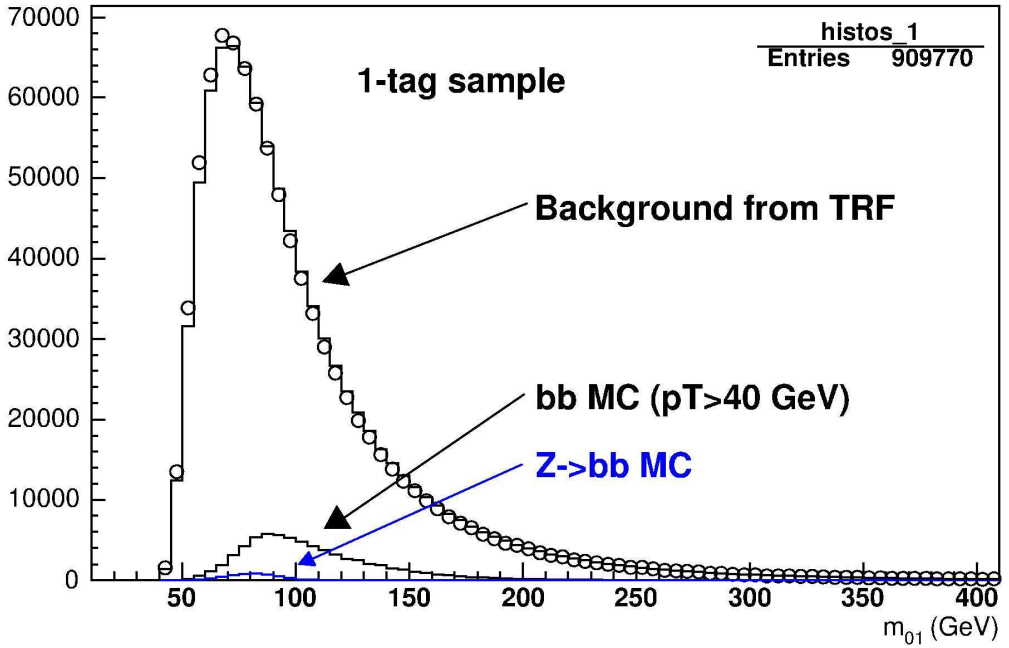
Purity ~ 85 % : extracted from data using shape of secondary vertex mass

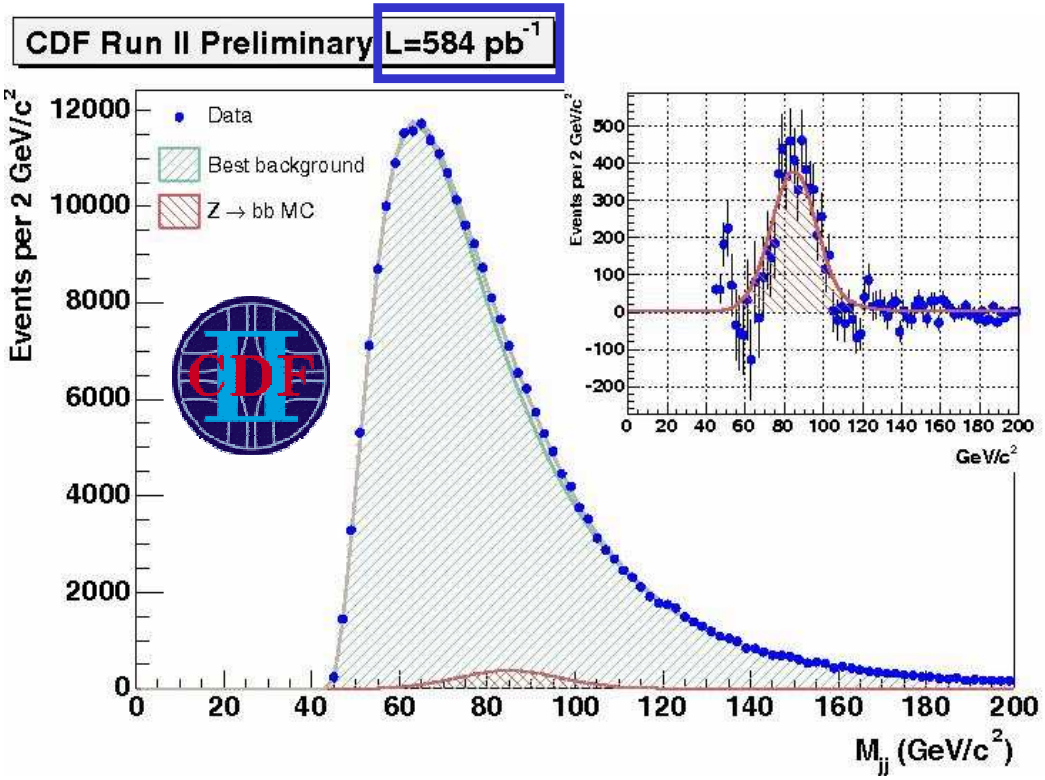


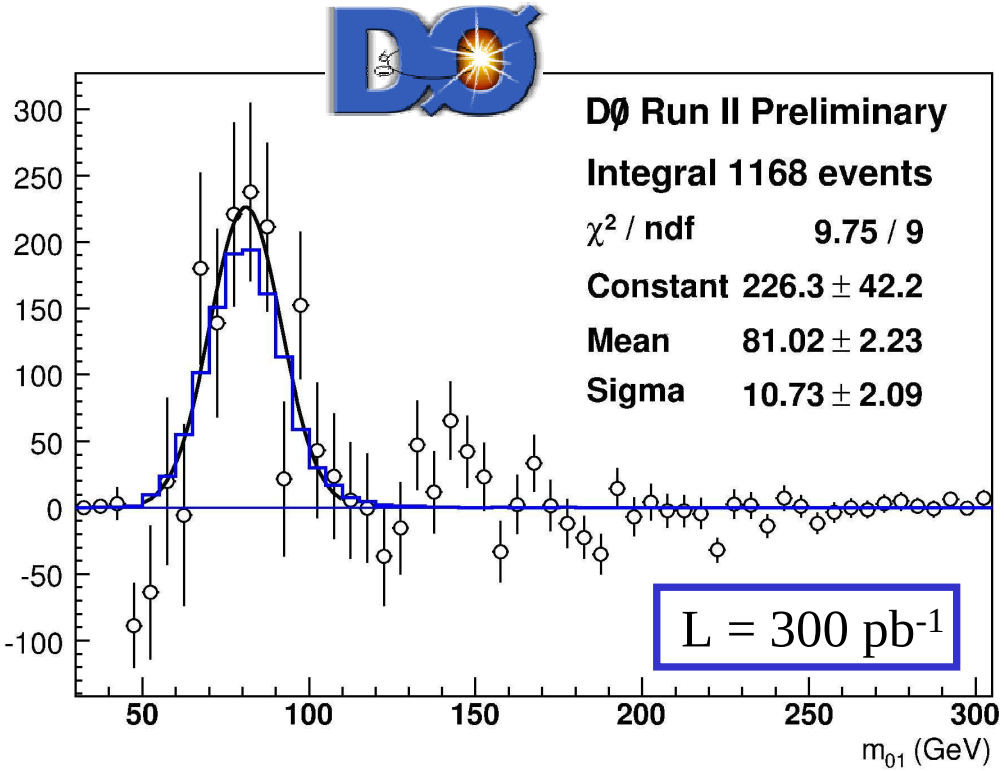


$Z \rightarrow b\bar{b}$

- Challenging due to very large background ($b\bar{b}$ and mis-tagged)
- Important to establish the b-jet energy scale
  - Also to check the $M_{b\bar{b}}$ resolution for low mass Higgs searches

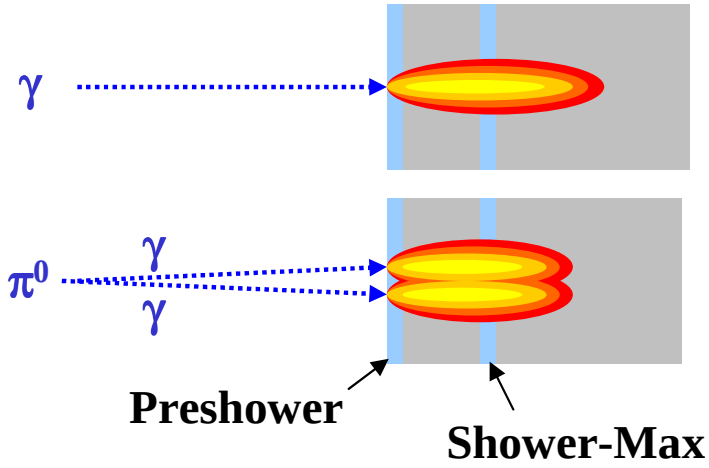


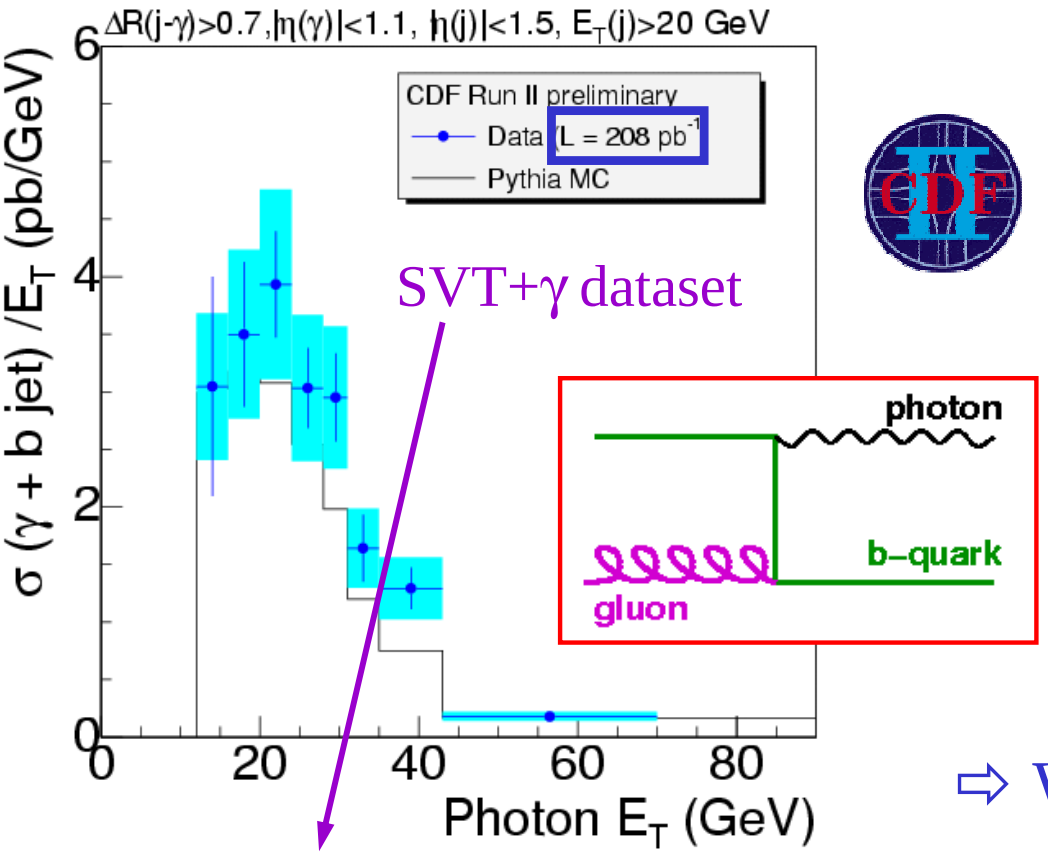




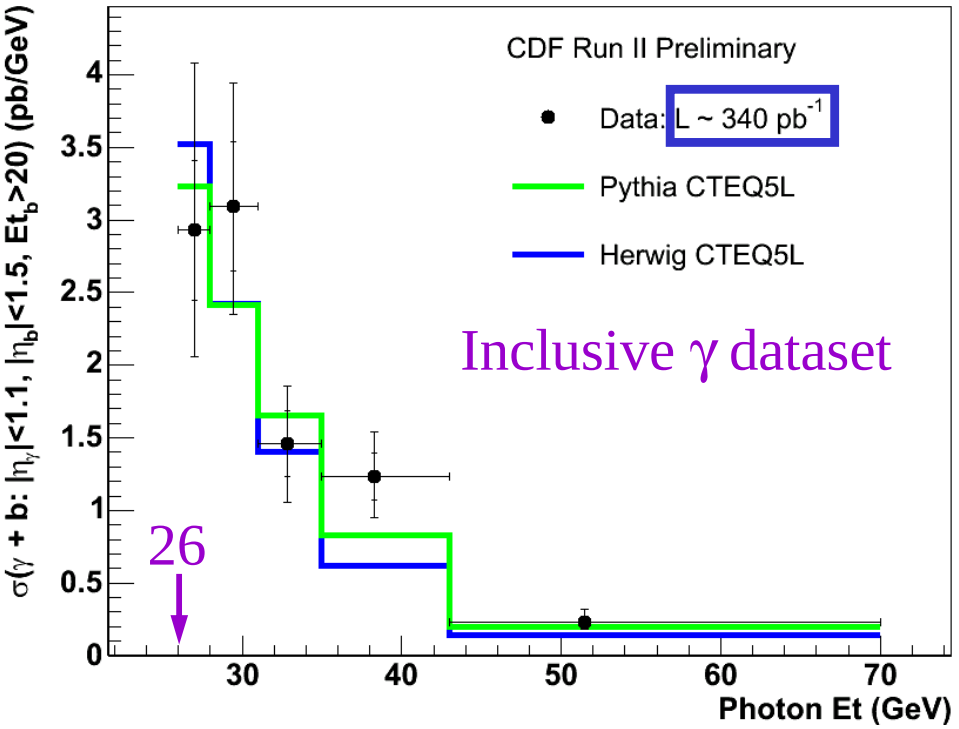
γ + b-jet

- Probes heavy-quark PDFs
- Background for SUSY (light stop)
- Experimentally difficult because of large background from π^0 decays





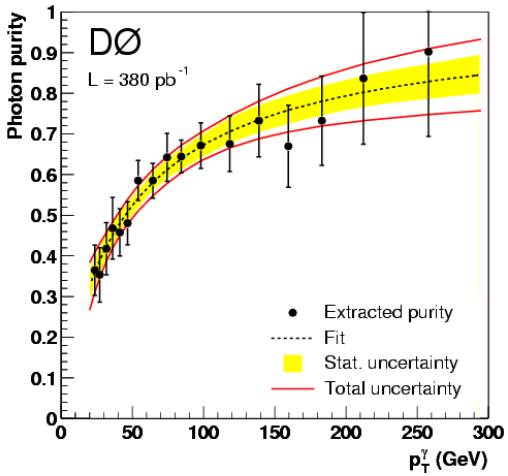
Lower E_T^{γ} thresholds to 12 GeV

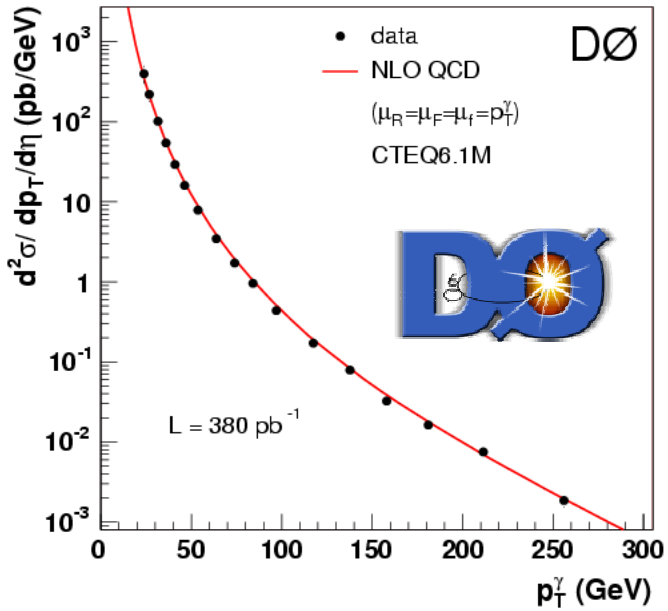


⇨ Working on comparison to NLO (based on JETPHOX)

Direct γ Production

- Precision test of pQCD
  - Well known coupling to quarks (QED)
  - QCD Compton dominates for $p_T^{\gamma} < 120$ GeV
    - Constrains gluon PDF (?)





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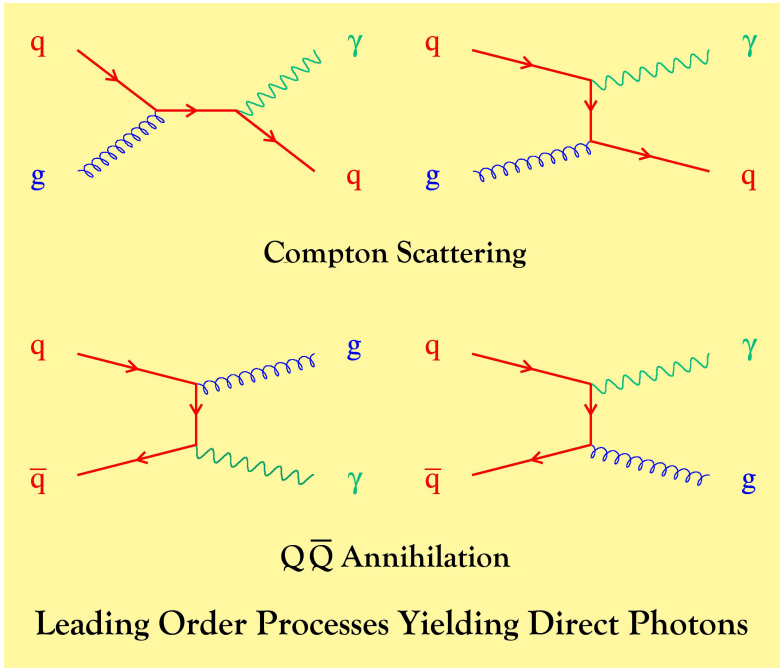
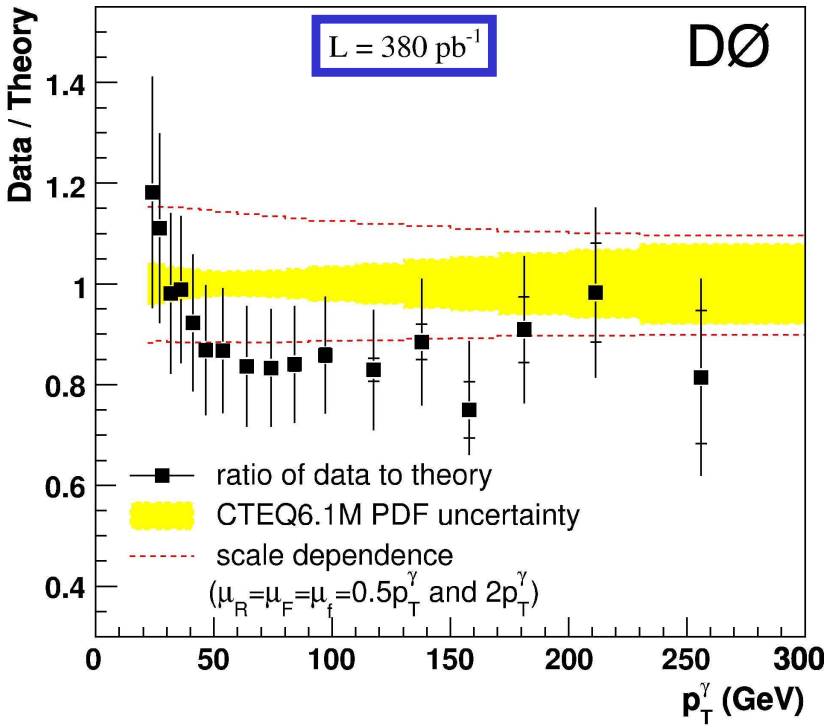
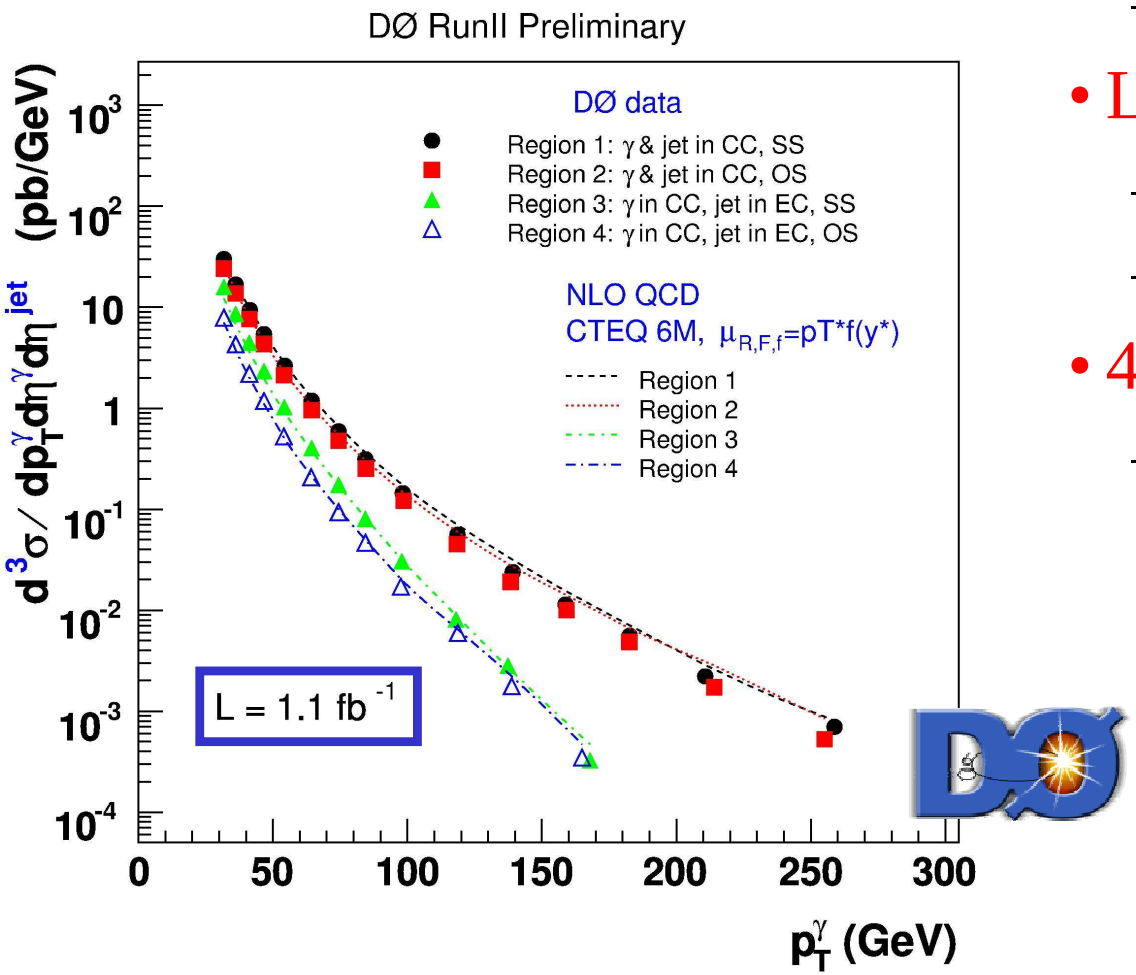


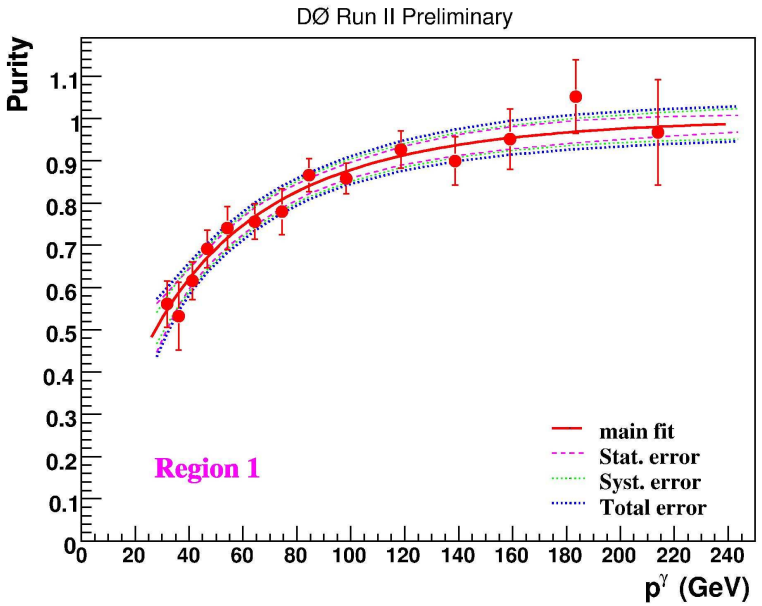


- Very promising at the 1-2 fb^{-1} level
  - But PDF sensitivity would also requires improved theory (resummation / NNLO)

γ+Jets



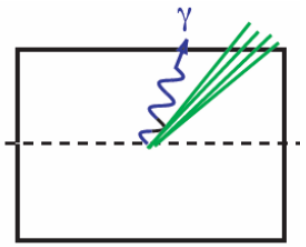
- Central isolated photon
  - $p_T^\gamma > 30$ GeV , $|\eta^\gamma| < 0.8$
- Leading jet: $p_T^{JET} > 15$ GeV
  - Central: $|\eta^{JET}| < 0.8$
  - or Forward: $1.5 < |\eta^{JET}| < 2.5$
- 4 regions
  - CC or CF events of 2 kinds
    - SS (Same Signs): $\eta^\gamma \times \eta^{JET} > 0$
    - OS (Opposite Signs): $\eta^\gamma \times \eta^{JET} < 0$



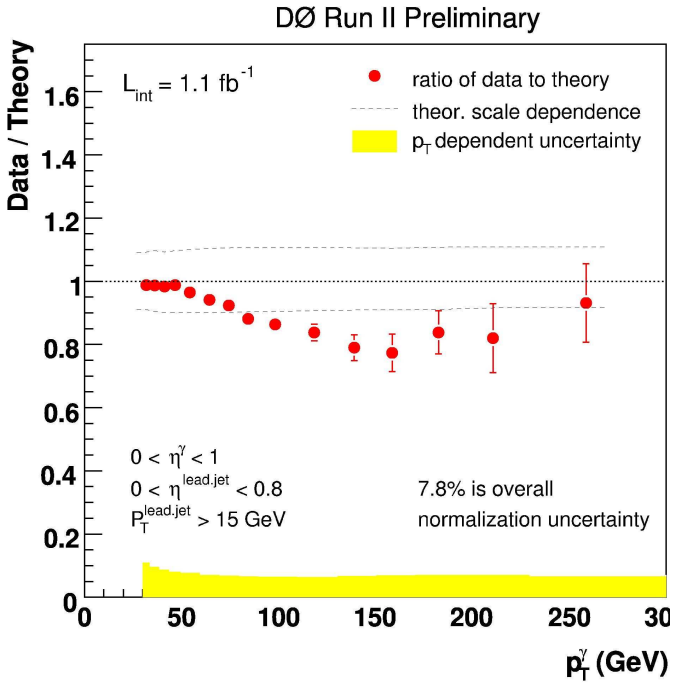
↳ Data compared to NLO pQCD

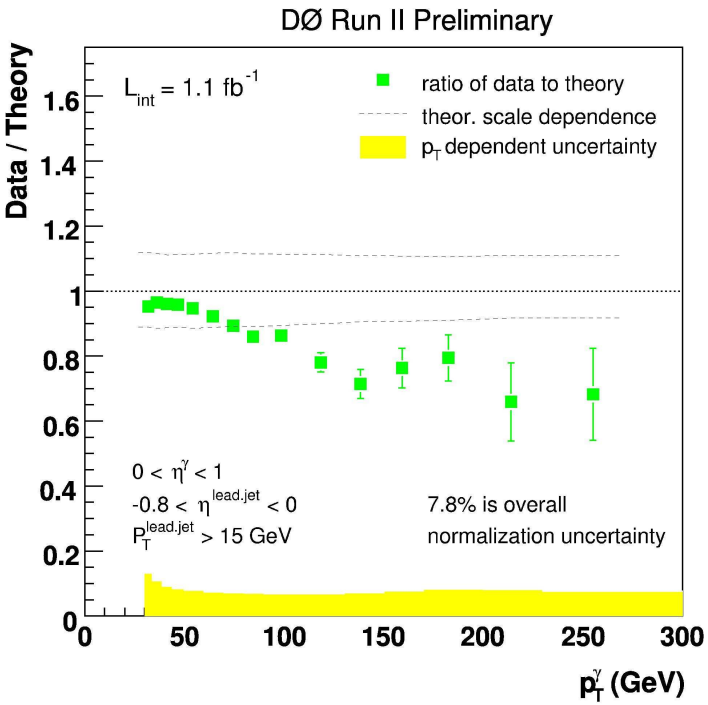
– JETPHOX with CTEQ6.1M PDFs and BFG Fragmentation Functions

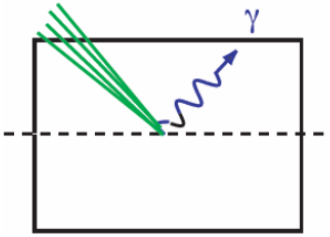
γ+Jets: Data / Theory



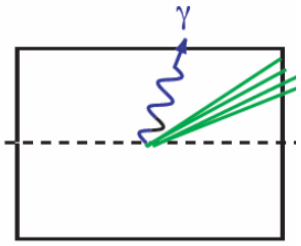
Region 1
CC / SS



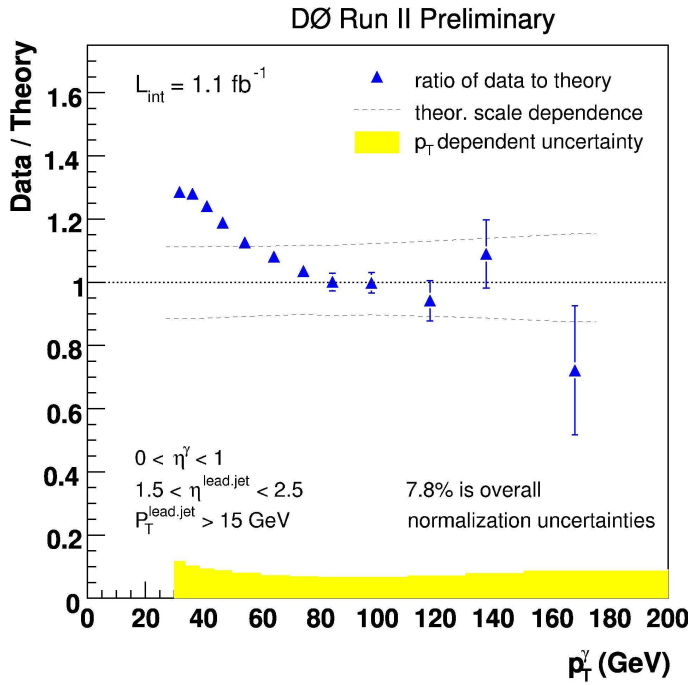


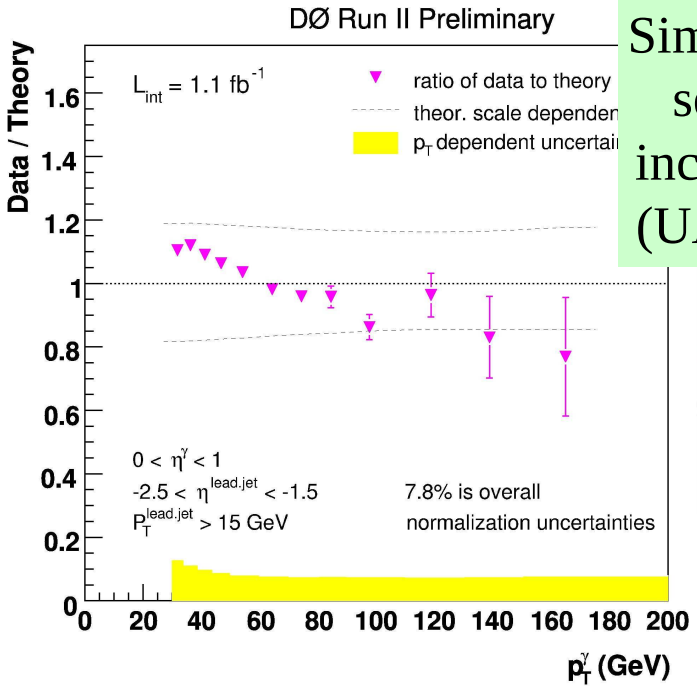


Region 2
CC / OS

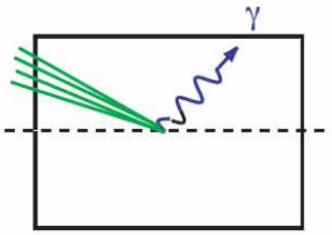


Region 3
CF / SS



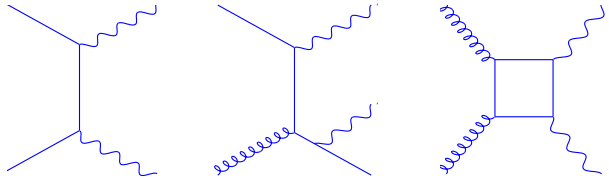


Similar deviations seen before in inclusive photons (UA2, CDF, DØ)



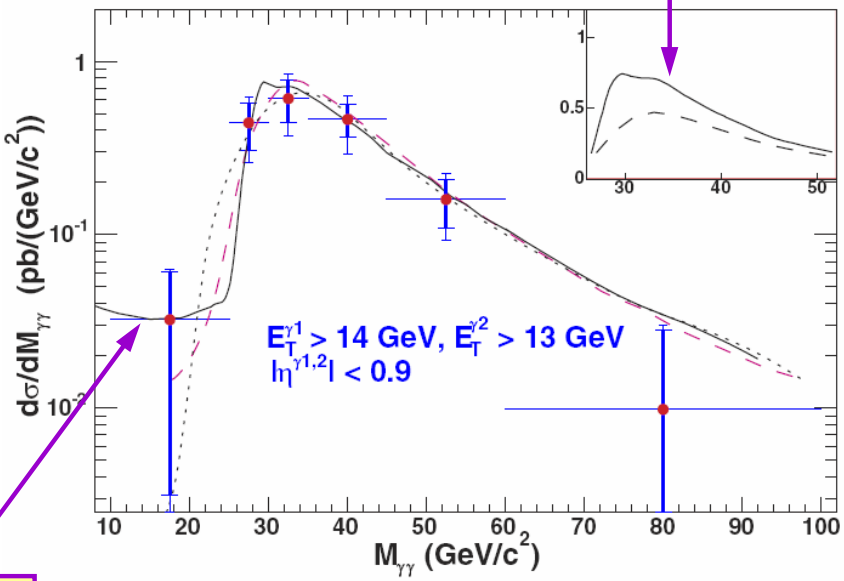
Region 4
CF / OS

Prompt γγ Production



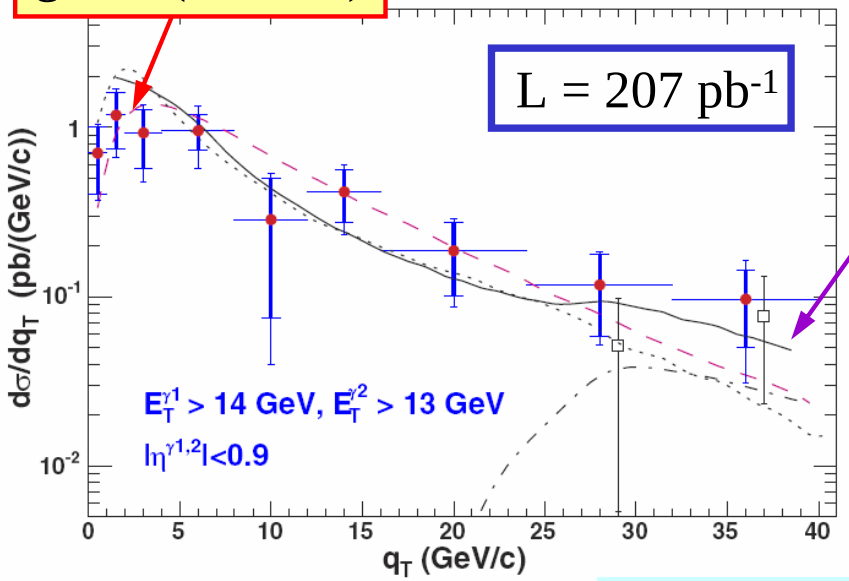
- DIPHOX (——)
  - NLO prompt γγ, NLO fragmentation
  - NNLO gg→γγ box diagram
- ResBos (- - -)
  - NLO prompt γγ, LO fragmentation
  - Resummed initial state gluon radiation
- PYTHIA (·····) scaled by factor 2

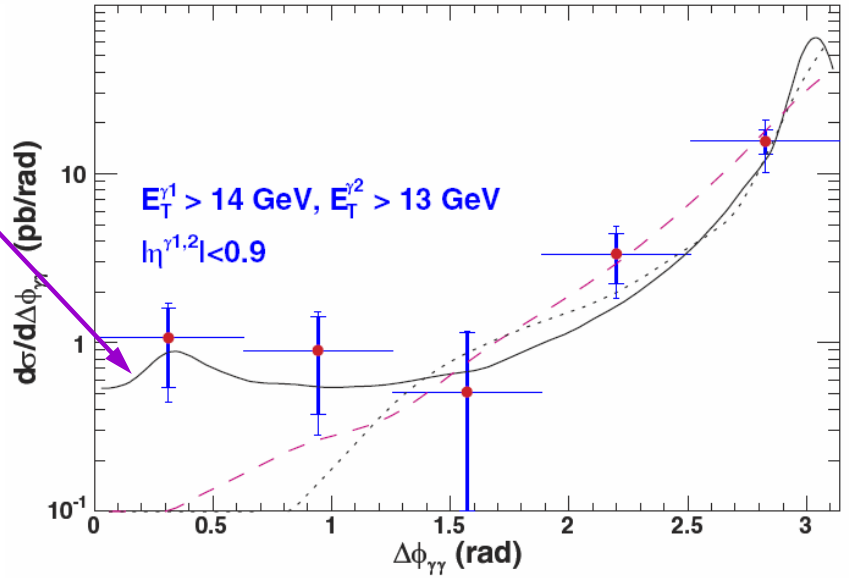
DIPHOX with & w/o NNLO gg-diagram



Res. initial-state gluon (ResBos)

NLO fragm. (DIPHOX)



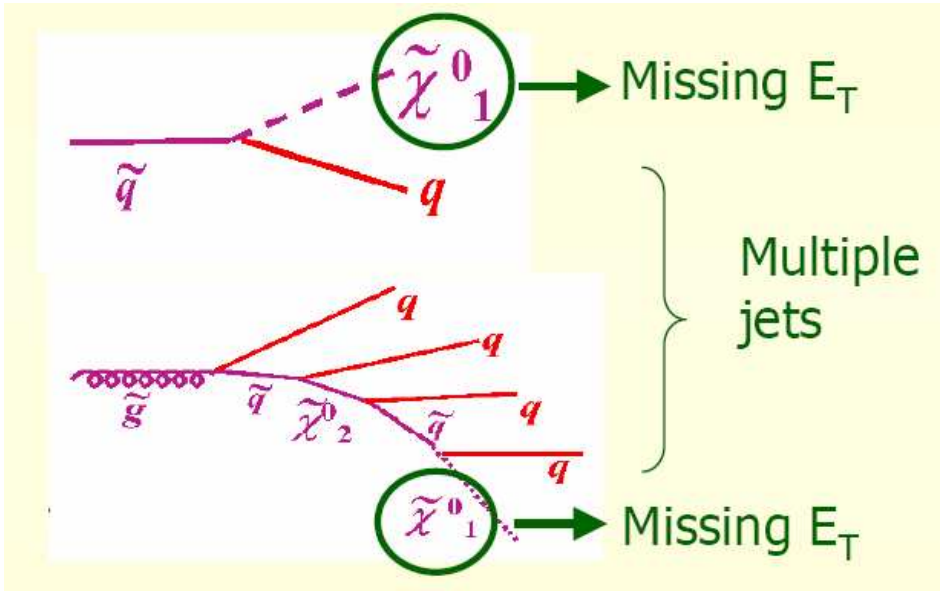


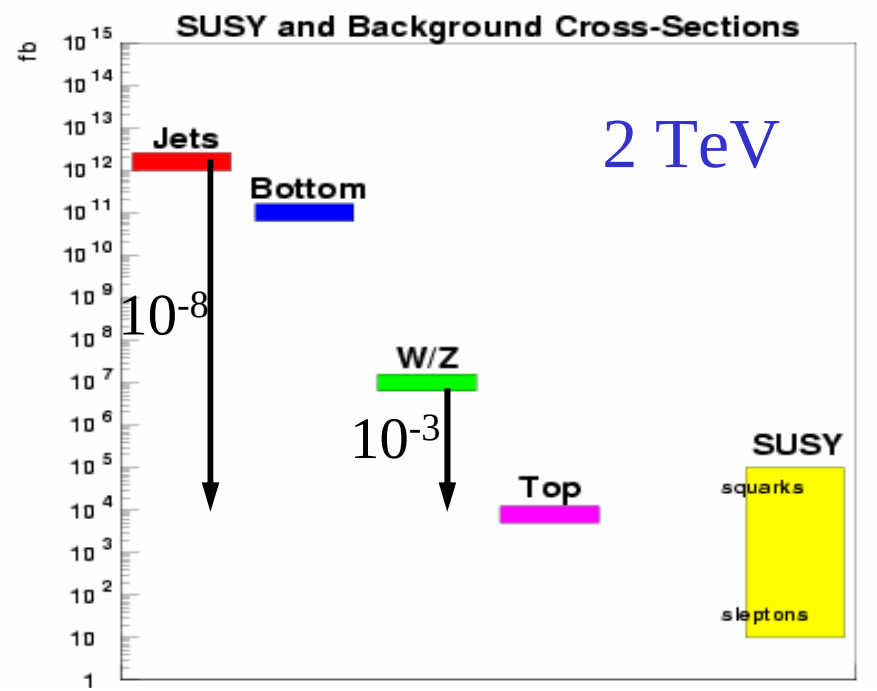
⇨ Important for Higgs search at the LHC

Phys. Rev. Lett. 95, 022003 (2005)

QCD & New Physics

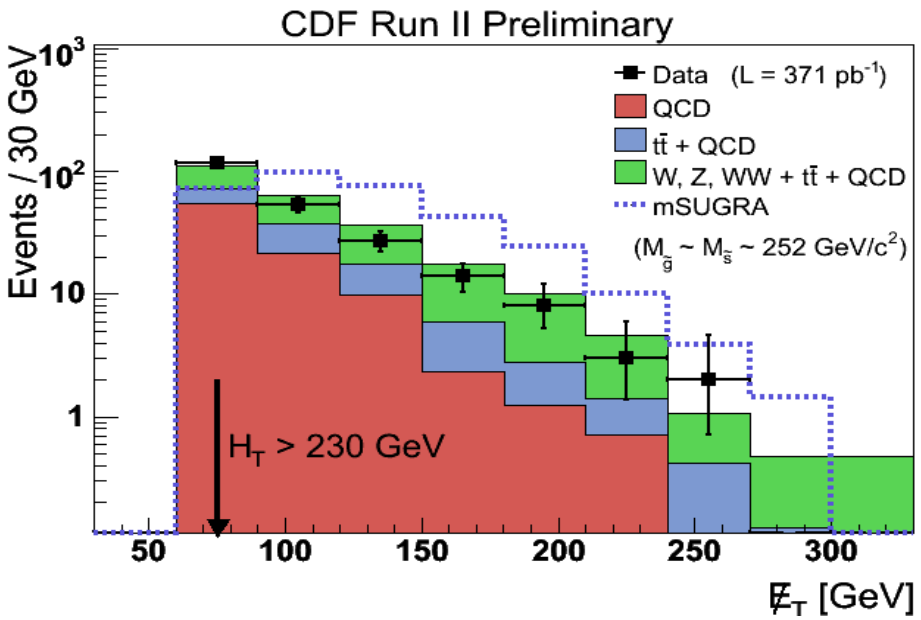
- SUSY in Missing E_T + Jets channel



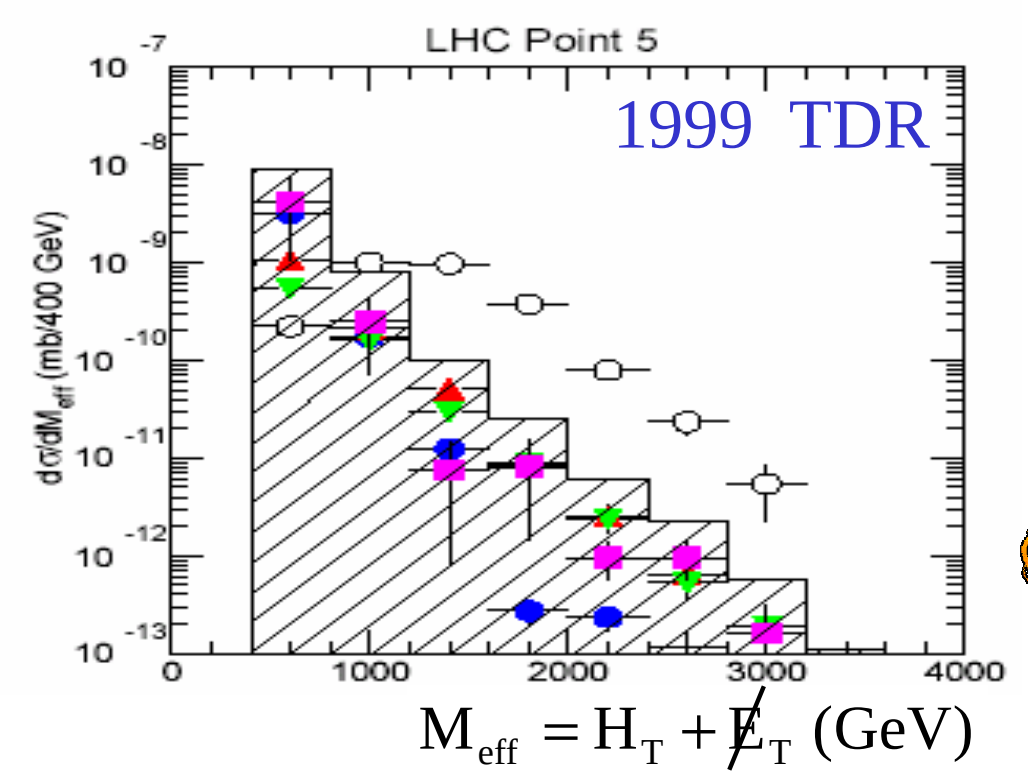


- Backgrounds
  - $Z \rightarrow \nu\nu$ + 3 jets
  - $W \rightarrow e\nu$ + 2/3 jets
  - $W \rightarrow \tau\nu$ + 2 jets
  - QCD, Top, WW...

⇨ Good understanding of Boson+Jets is mandatory

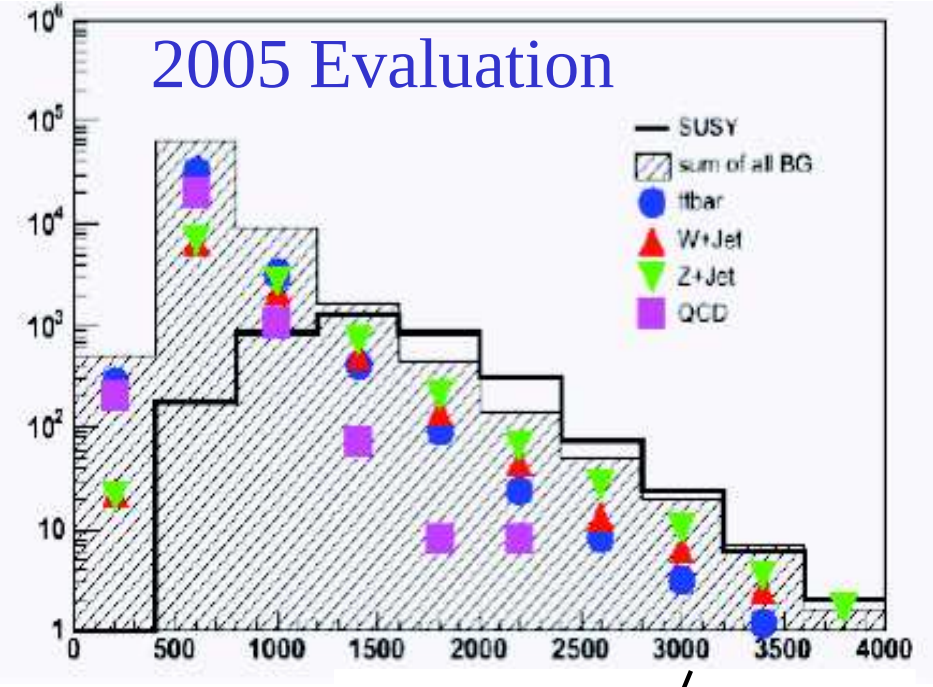


Towards SUSY at the LHC



1999 ATLAS TDR

Preliminary MC studies suggested very good SUSY discovery potential in the Missing E_T + Jets channel



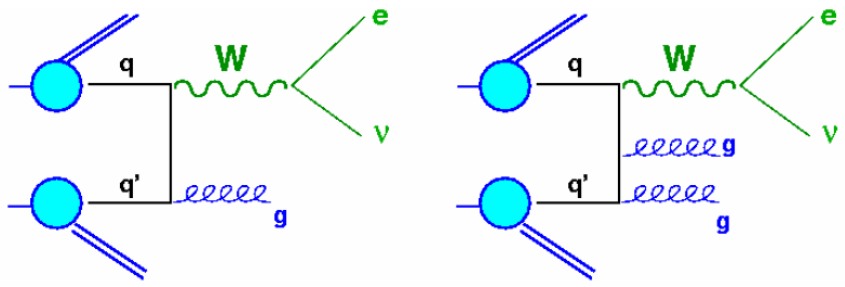
2005 Evaluation

New W/Z+Jets programs predict much harder jet p_T spectrums than Pythia which was previously used

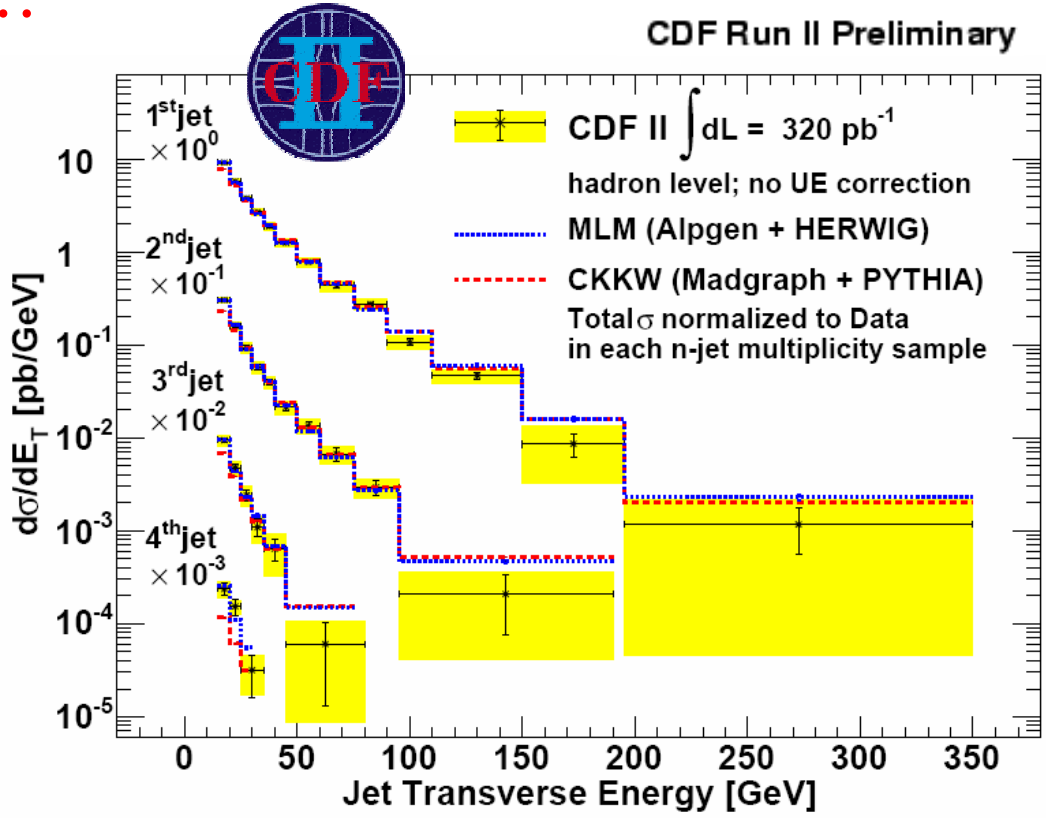
⇨ Dramatically changes the picture

W+Jets Production

- Test Ground for Matrix Element + Parton Shower (ME+PS) techniques
  - Special matching (MLM, CKKW) to avoid double counting
- Background of top, Higgs, SUSY…
- $W \rightarrow e\nu$ + Jets
  - Run I cone based algorithm (JetClu) with R=0.4
    - $E_T^{JET} > 15$ GeV
    - $|\eta^{JET}| < 2$
  - L = 320 pb^{-1}
- Shapes comparison to different Leading Order ME+PS predictions
  - Fair description of the n^{th} E_T^{JET} shapes in the different n-jet multiplicities



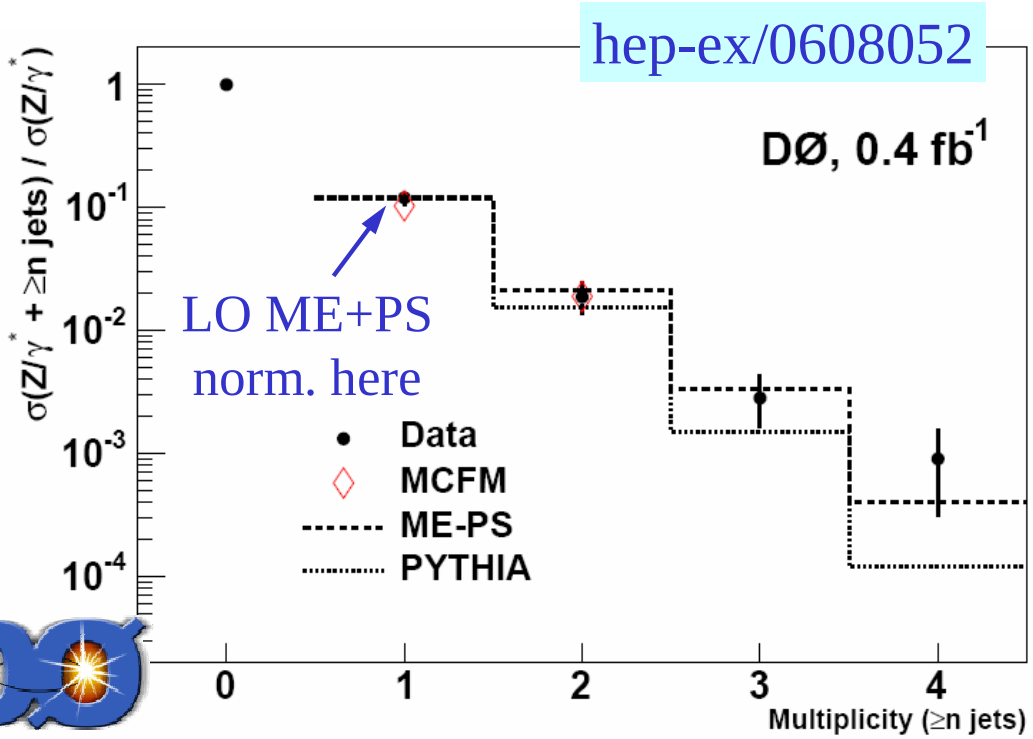
… + PS

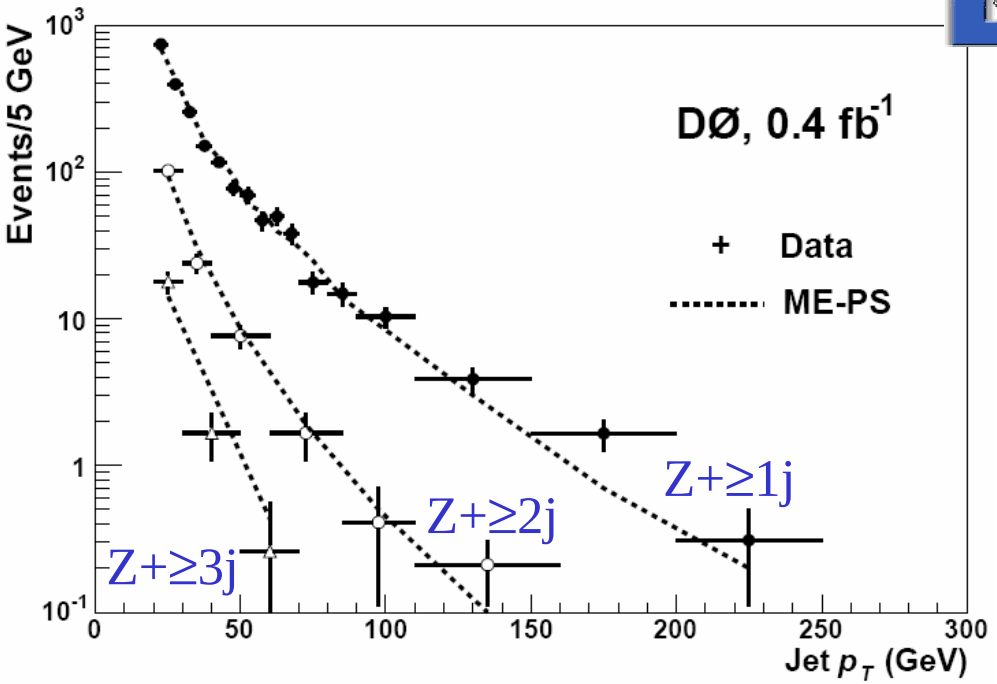


Z+Jets Production

- Almost background free
  - Cross section ~ W+Jets / 10
- $Z \rightarrow ee$ + Jets
  - Run II cone based algorithm (Midpoint) with R=0.5
    - $p_T^{JET} > 20$ GeV ; $|\eta^{JET}| < 2.5$
  - L = 0.4 fb^{-1}

hep-ex/0608052

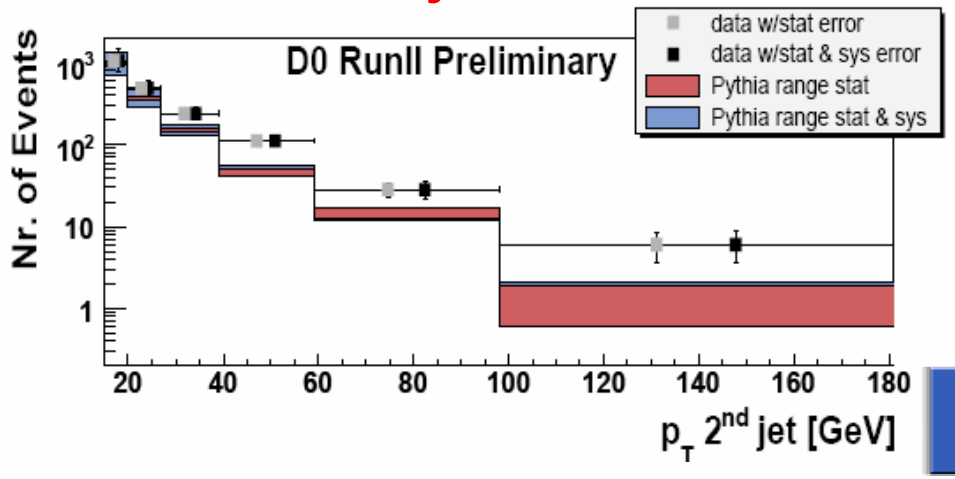




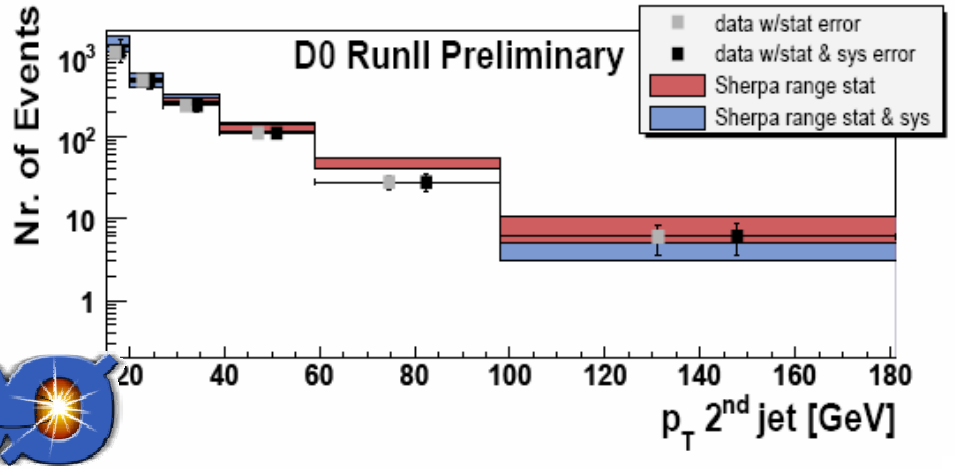
- NLO for Z+1p and Z+2p: MCFM
  - Well describe measured cross sections
- LO ME+PS: Madgraph + Pythia with CKKW matching
  - Reproduces the n^{th} p_T^{JET} shapes
    - LO generated up to Z+3p (additional jets from PS)

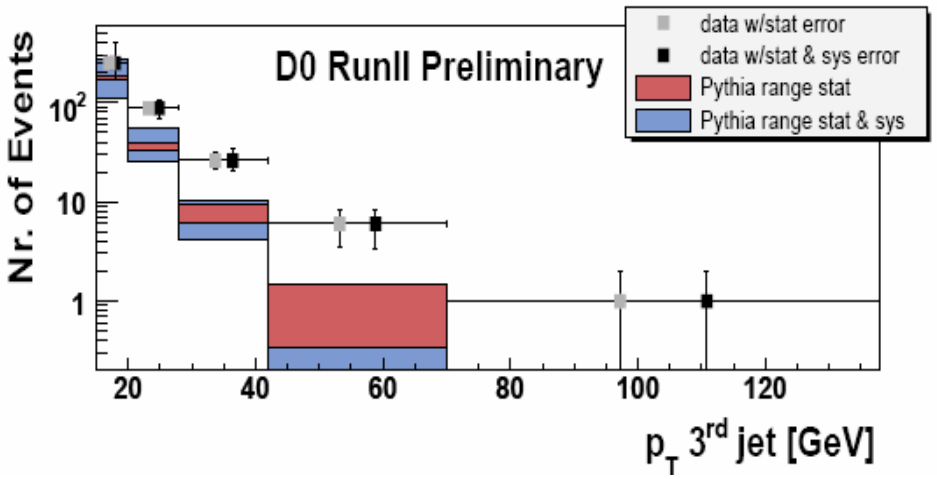
Z+Jets comparison to MC

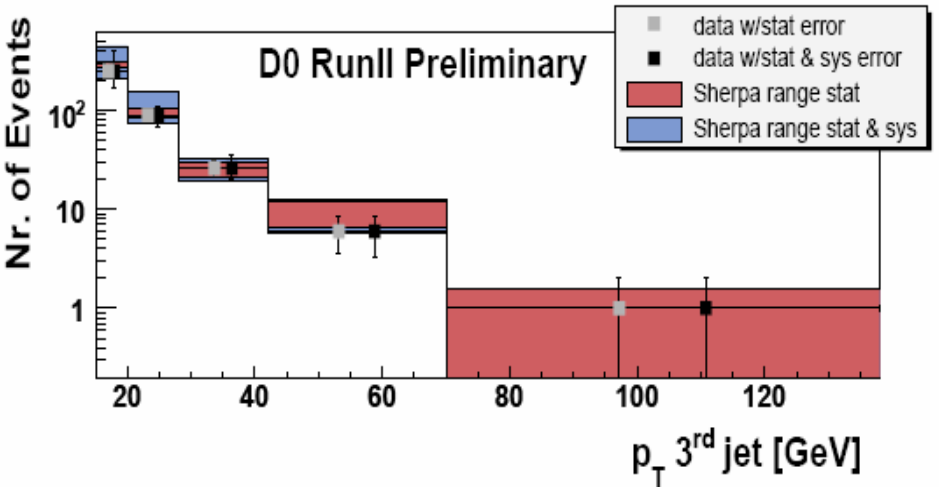
Pythia



Sherpa







L = 0.95 fb^{-1}: Z → ee + Jets

– Midpoint with R=0.5

• $p_T^{JET} > 15$ GeV ; $|\eta^{JET}| < 2.5$

⇨ Pythia off for 2nd and 3rd jet p_T

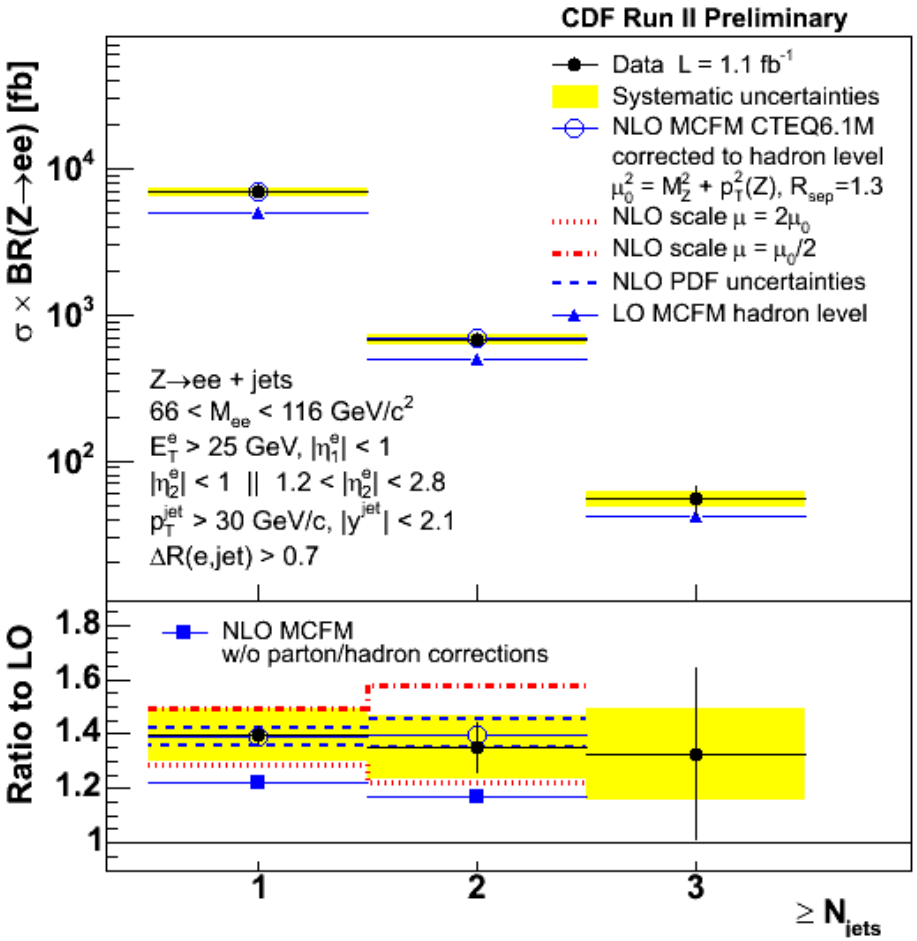
⇨ Sherpa (based on CKKW) provides a good description of the data

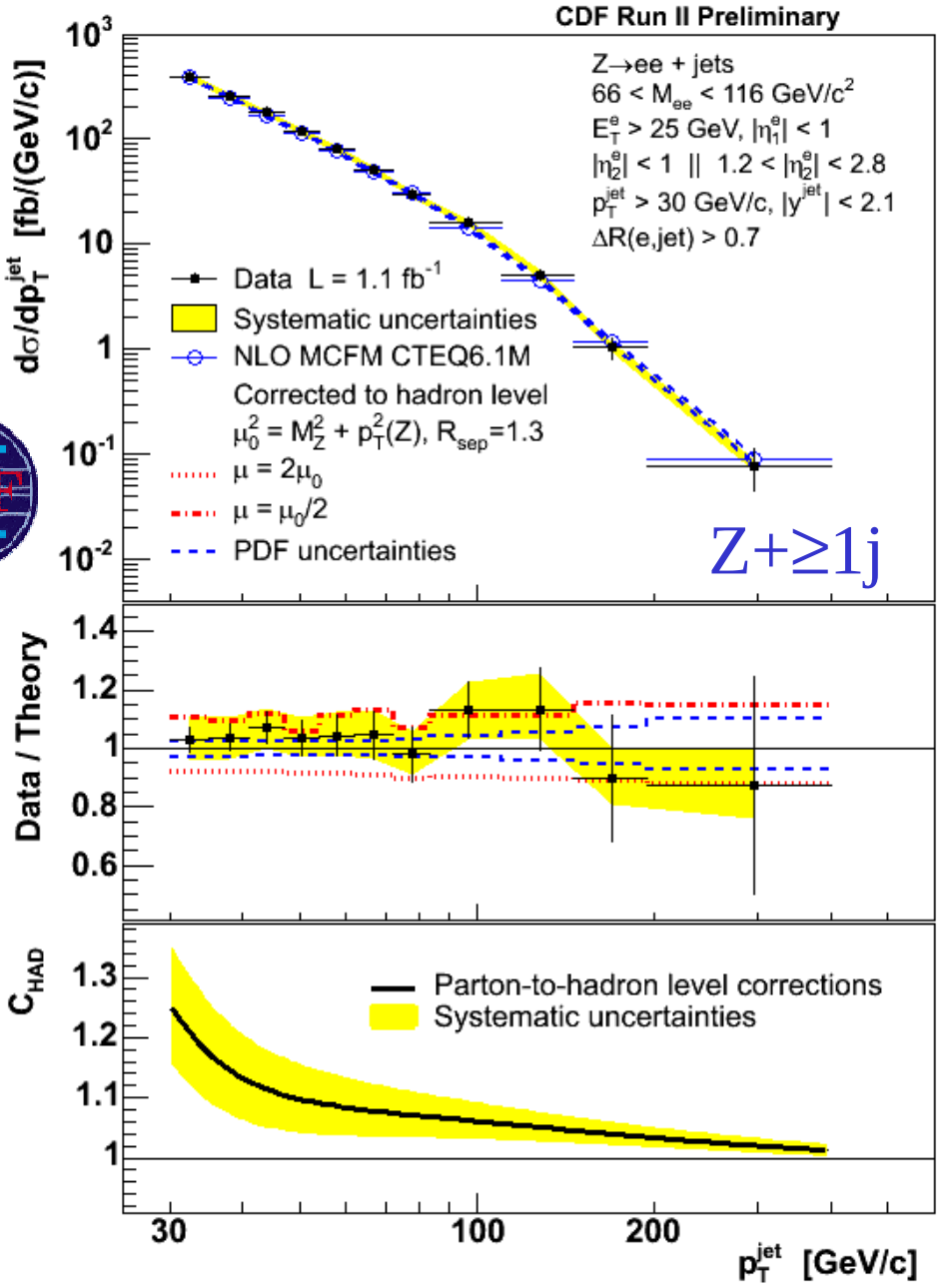
Z+Jets at CDF

L = 1.1 fb^{-1}: Z → ee + Jets

– Midpoint with R=0.7

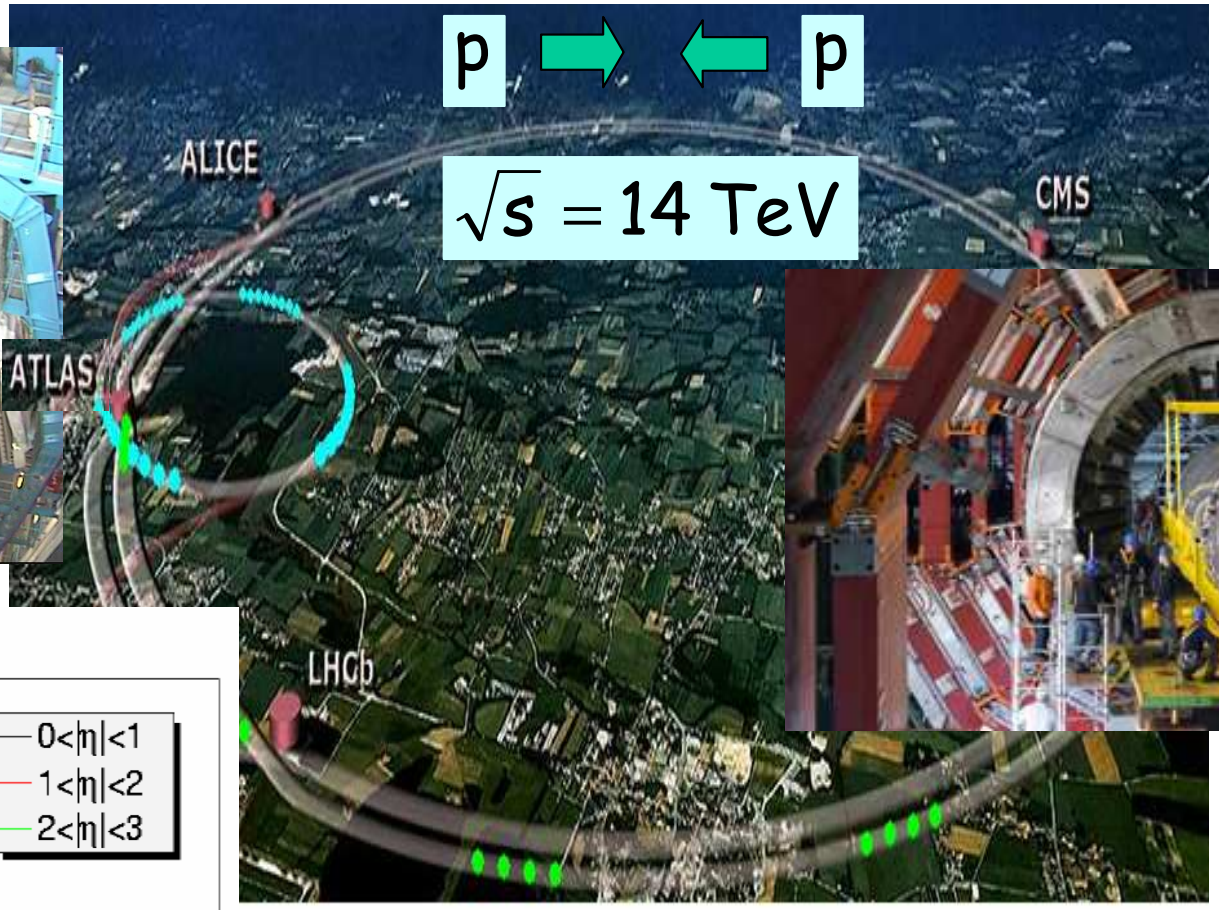
• $p_T^{JET} > 30$ GeV ; $|y^{JET}| < 2.1$

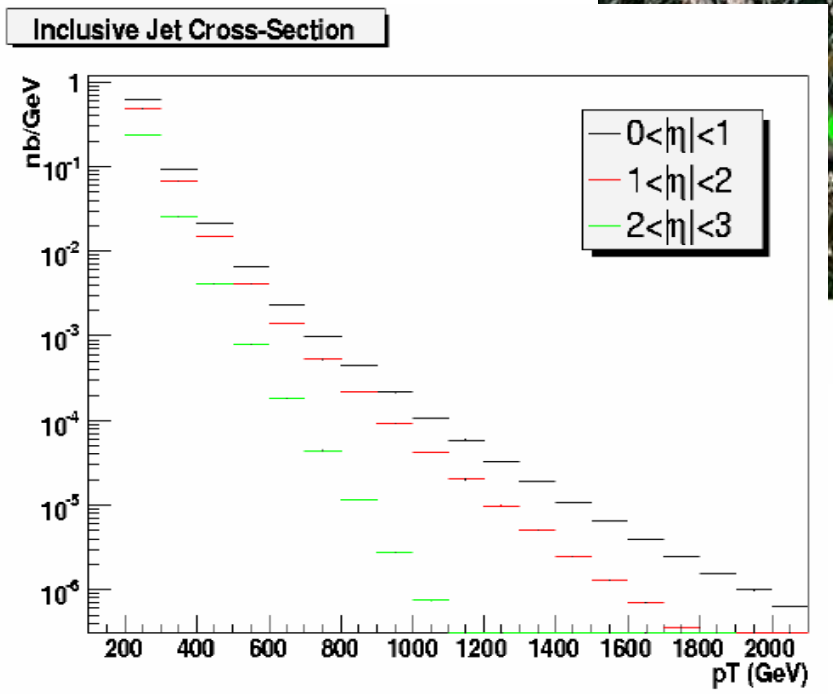




⇨ Good agreement with NLO

LHC





Expect few jets above 2 TeV for 0.1 fb^{-1}

⇨ First Results in 2009 (?) …

Outlooks

- HERA is ending
  - Full dataset analyses and F_L results to come
  - Jet measurements at HERA
    - Constitute stringent tests of pQCD
    - Provide precise measurements of α_S and its running
    - Allow to better constraint the gluon PDF
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  - Precision tests of pQCD with prompt γ and prompt $\gamma\gamma$ productions
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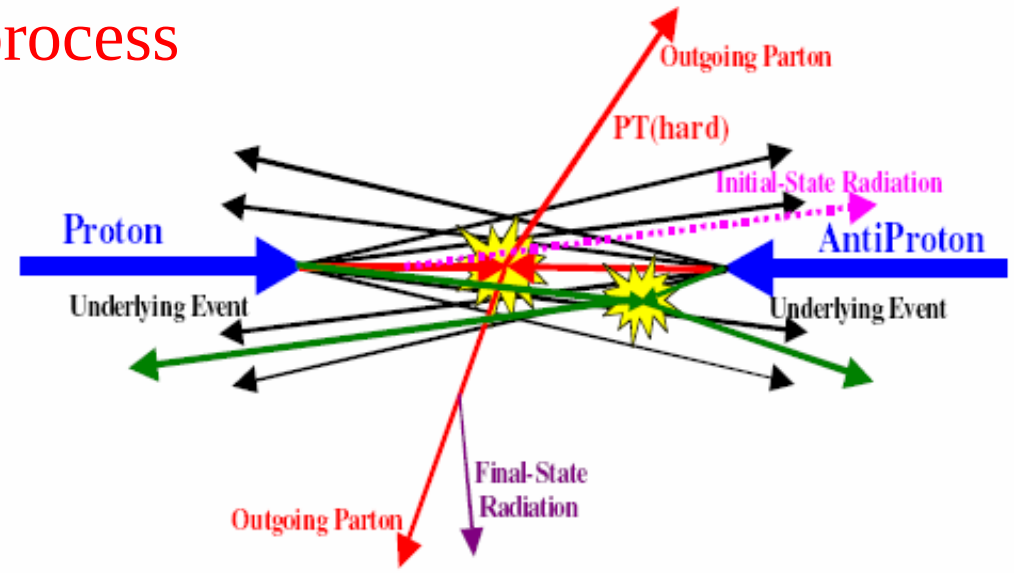
First LHC results in 2009 …

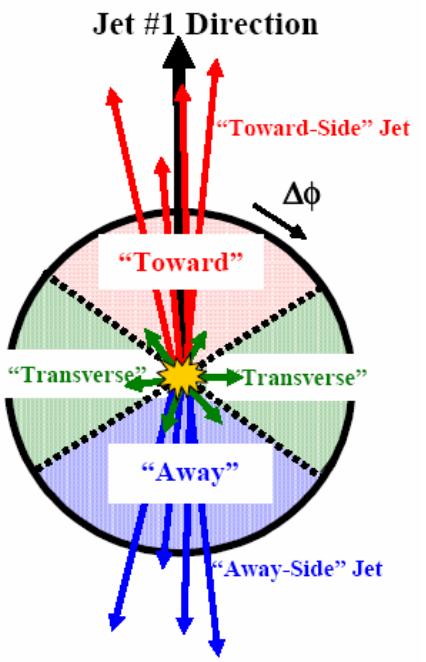
… a new era

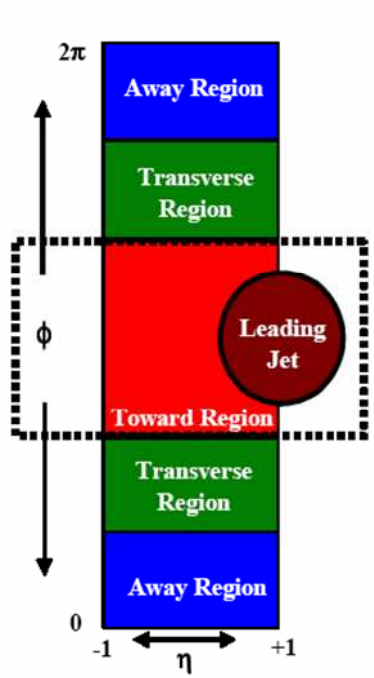
Backup Slides

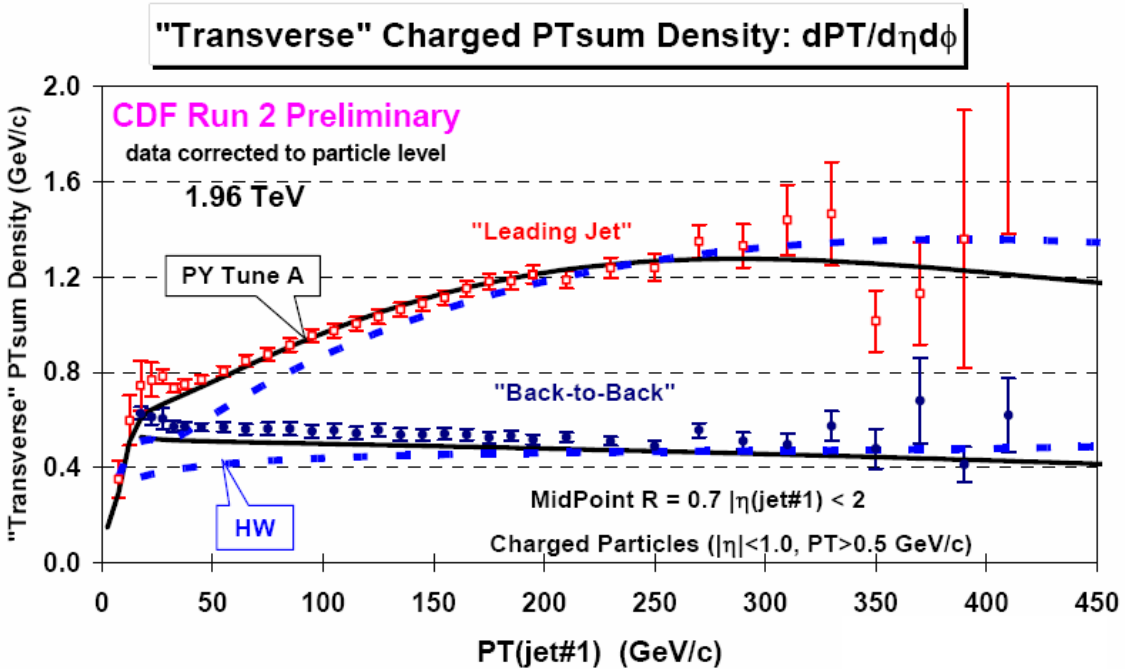
Underlying Event

- Everything but the hard scattering process
  - Initial state soft radiations
  - Beam-beam remnants
  - Multiple Parton Interactions (MPI)
- Studied in the transverse region
  - Leading jet sample
  - Back-to-back sample





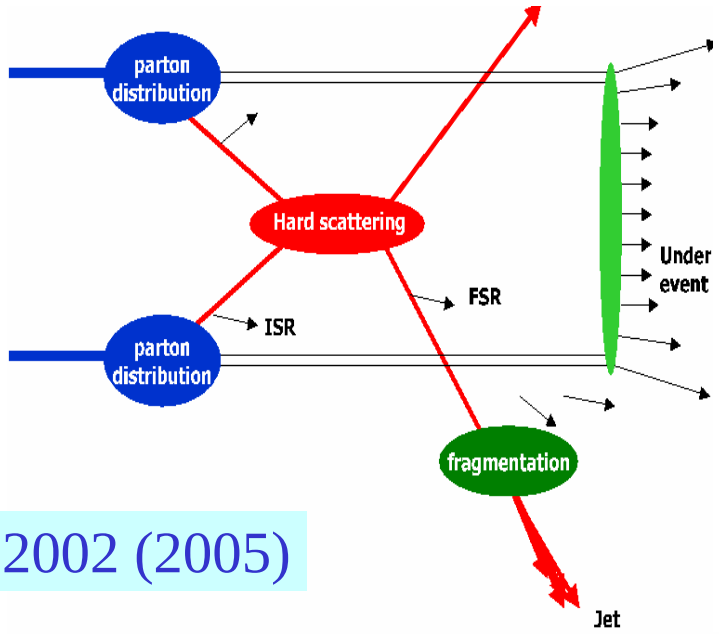




Energy Flow Inside Jets

Jet shapes governed by multi-gluon emission from primary parton

- Test of parton shower models
- Sensitive to underlying event structure
- Sensitive to quark and gluon mixture in the final state



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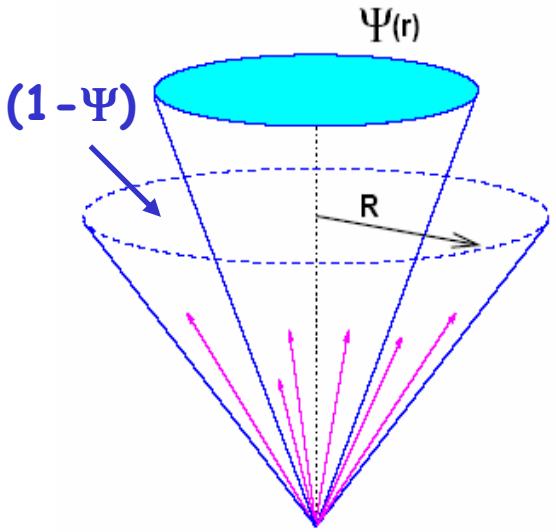
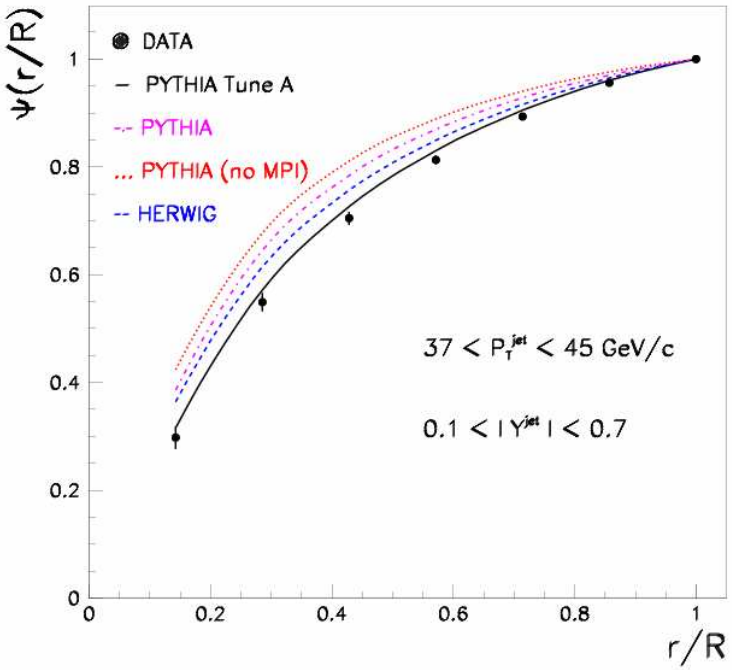
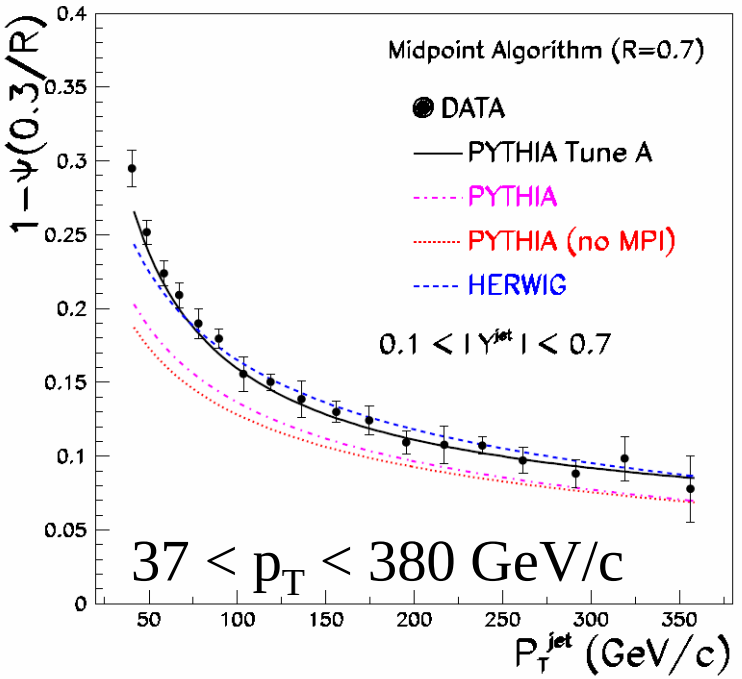
$$\Psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{P_T(0,r)}{P_T(0,R)}$$







Results from ZEUS / D0 Run I